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MATHEMATICAL MODEL FOR ESTIMATING TRANSIENT PRESSURE
SURGES IN CRYOGENIC LIQUID-VAPOR SYSTEMS

BY

PHILIPPE PFISTER
B.S., Ecole Centrale de Lyon, FRANCE, 1980

THESIS

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ABSTRACT

Numerical treatments have become the most accurate methods for transient liquid flows analysis. Based on a computer code provided by NASA/KSC, this paper presents two simulations of cryogenic transfer systems. Experimental data originated from the Space Shuttle Liquid Oxygen Servicing were obtained during drain flows. Two sets of data (pressure at various locations versus time) corresponding to a drain stop and a drain initiation were used for a comparison with the predicted pressures. The first test case was a single-phase flow whereas the second one was associated with liquid-column separation and vapor cavity collapse. Major modifications were made to the computer program for two-phase flow treatments. Encouraging results have been obtained validating the model and opening new perspectives for future work.

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NOMENCLATURE

A:	area of pipe
a:	speed of pressure pulse
C_D :	orifice discharge coefficient
D:	pipe diameter
E:	modulus of elasticity
e:	pipe-wall thickness
f:	Darcy-Weisback friction factor
g:	gravitational acceleration
H_p :	piezometric head at unknown computational point in (x,t) plane
J:	subscript denoting a particular pipe
K:	bulk modulus of elasticity
L:	pipe length
o:	subscript referring to steady-state conditions
p:	pressure
R:	hydraulic radius
r:	pipe radius
t:	time
V:	instantaneous velocity
V_o :	initial fluid velocity (steady state or mean)
V_p :	velocity at unknown computational point in (x,t) plane
x:	distance along pipe from left end
Z:	elevation of pipe above datum
α :	channel slope
θ :	characteristic grid-mesh ratio $\frac{\Delta t}{\Delta x}$
μ :	Poisson's ratio
v:	kinematic velocity
ρ :	mean density
σ :	unit stress in tube wall
τ :	discharge coefficient $C_D A / C_{D_o} A_o$
τ_o :	wall shear stress

INTRODUCTION

The space shuttle liquid oxygen servicing system is designed to transfer liquid oxygen (LOX) between the ground storage tank (S.T.) and the shuttle's external tank (E.T.). Figure 1 gives a schematic representation of this system. Detailed information on the system is given in Appendix D.

Within cryogenic liquid transfer systems, vapor cavities are easily formed if the fluid is maintained at conditions close to saturation and a small local reduction in pressure occurs. Any valve opening or closure may cause the cavities to form or collapse due to a pressure variation. The collapse of an entrapped vapor cavity provokes a waterhammer-type effect and the creation of high pressure waves. These pressure waves may damage the piping system, and associated instrumentation. To predict the magnitude of undesirable pressure surges, a transient waterhammer-type analysis is often required. Unfortunately, the analysis of pressure-wave behavior in cryogenic two-phase systems is phenomenologically complex.

The objectives of the present study are to develop a mathematical model that may be used for the prediction of pressure behavior in single- and two-phase LOX systems and validate the model by comparison with experimental data obtained during previous space shuttle operations.

Chapter 1, of this report, gives a general description of water-hammer-type behavior including the effects of pipe elasticity and vapor entrainment. In Chapter 2, the method of approach and the basic theory underlying the physical process of transient flow in conduits are presented. The results are detailed and discussed in Chapter 3. Chapter 4 concludes the work and provides suggestions for future work.

CHAPTER I

FUNDAMENTALS OF WATERHAMMER

Transient pressure surges are inherently undesirable within a complex fluid transport system. A rapid increase in local system pressure may be sufficiently great to jeopardize the integrity of the system piping and/or associated system components. A general understanding, therefore, of the pressure wave generation process is necessary for the proper design and operation of such systems.

The formation and propagation of pressure waves within a system are the result of complex hydraulic-system interactions. The thermophysical nature of the fluid (temperature, density, phase, sonic velocity, etc.) and the piping system (diameter, wall thickness, elasticity, etc.) in tandem with the operational scenario (valve sequences, pump demands, etc.) govern the occurrence, amplitude and dissipation of transient pressure waves.

The concept of rapid unsteady flow, i.e., the flow rate at a point that changes suddenly with time, is called waterhammer. The flow is considered as being transient while changing from one steady state condition to another. Transient behavior may be generated by rapid valve closure (or opening) or by the collapse of a vapor cavity. It is always accompanied by a change in fluid velocity at a specific point, and sometimes by pressure surges which may be large enough to have damaging effects on the piping system. The equation relating a change in

velocity to a pressure head change is derived within Streeter and Wylie (1967) and has the following form:

$$\Delta H = \frac{a}{g} \Delta V \quad (1)$$

where:

ΔH : change in pressure head

ΔV : change in velocity

a : wavespeed of the fluid in the pipe

g : gravitational acceleration

(For LOX in thin-walled pipelines a is of the order of 2,600 ft/s

so that $\frac{a}{g} \approx 80$ sec. Therefore a sudden reduction in velocity of 1 ft/sec yields a head rise of 80 ft head.)

To visualize the mechanism of wave propagation and reflection at a boundary, the following example of a horizontal pipe connected upstream to a reservoir and downstream to a fast-closing valve is discussed (Figure 2).

The valve is closed at time $t = 0$ and the fluid upstream starts being compressed and is brought to rest while the pipe wall is stretched. This process is repeated gradually for all the layers within the pipe in direction to the reservoir at the wavespeed a , bringing the fluid to rest as it compresses and expanding the pipe walls (Figure 2a). At time $t = \frac{L}{a}$ where L is the pipe length, the wave reaches the upstream end of the pipe leaving the entire fluid under the extra head H after having converted the total kinetic energy into elastic energy (plastic deformations and friction losses are not considered in this simplified example).

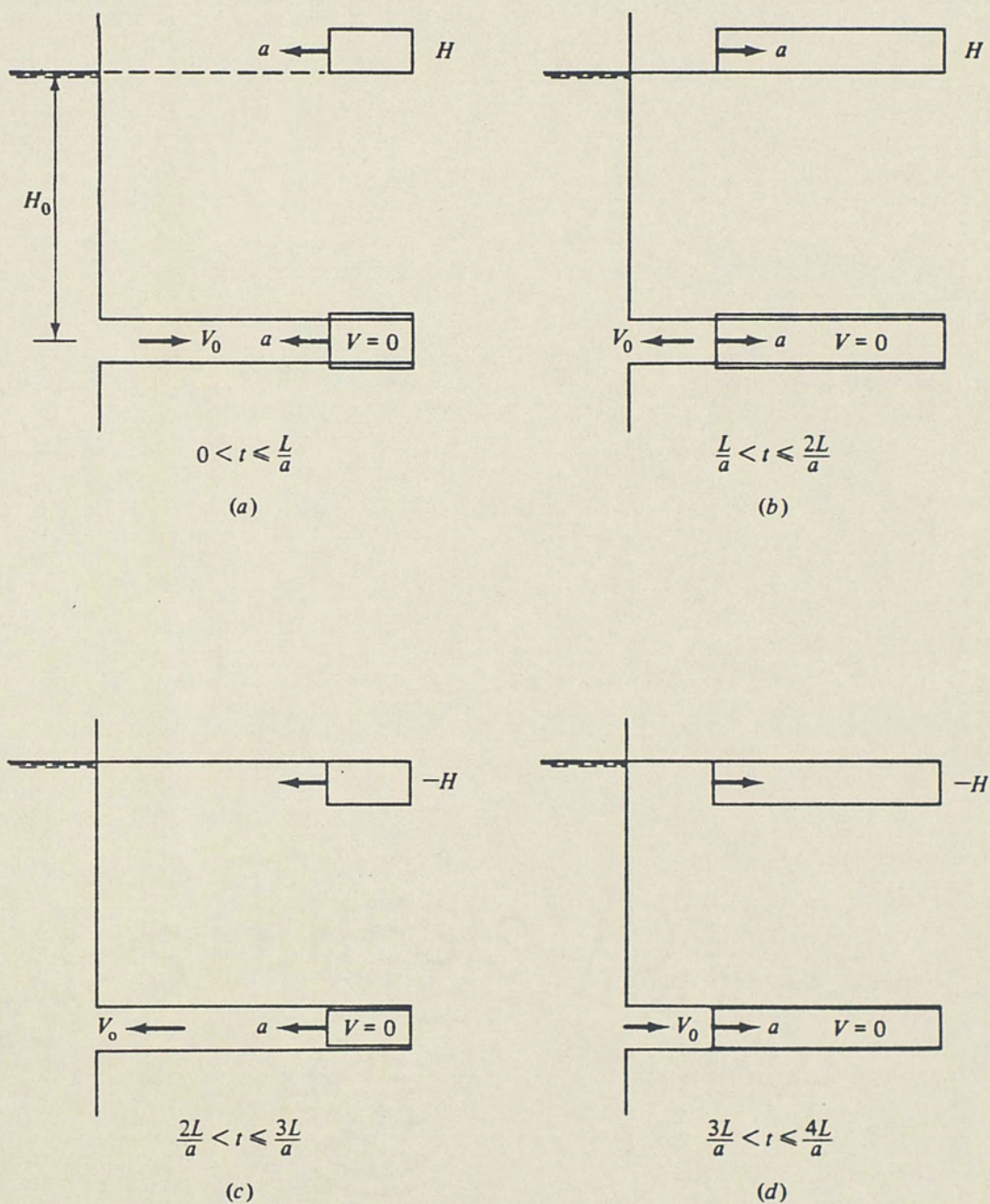


Fig. 2. Sequence of events after sudden closure of a valve.

At the reservoir, however, the pressure still has its initial value and the nearest fluid layers to the tank are in unbalanced condition. Therefore, the fluid starts to flow backward into the reservoir, decompressing the fluid at the reservoir entrance until the pressure again takes its normal value it had before closure. The fluid gets the same velocity it had before closure, but in the opposite direction, and the pipe walls return to normal (Figure 2b). At time $t = \frac{2L}{a}$ the wave returns to the valve, pressures return to normal everywhere and the velocity is everywhere negative with a speed numerically equal to the original velocity.

Since the valve is closed, no fluid is available to maintain the flow and a low-pressure ($-H$) is created and brings the flow to rest. Travelling at a speed "a" towards the tank, this low pressure wave contracts the pipe walls while at the same time expanding the fluid (Figure 2c). If the fluid static pressure becomes less than vapor pressure (and for cryogenic fluid it is often the case) vapor formation occurs.

At time $t = \frac{3L}{a}$ the layers close to the tank are set at rest but in unbalanced pressure condition since the pressure downstream is at head $-H$ less than the upstream layers. The fluid again flows with the initial velocity in the direction of the valve leaving a normal pressure behind the front wave travelling at speed a (Figure 2d). Finally the wave reaches the valve at the instant $t = \frac{4L}{a}$ and all the conditions are similar to those at time $t = 0$. This periodic process (the period

is $4 L/a$) in reality is damped out by friction and plastic deformation; eventually bringing the fluid to rest.

Wavespeed a

The wavespeed is a dominant factor which influences the pressure head. It depends on the piping system and the nature of the fluid itself. A general relationship for wavespeed is given by Streeter and Wylie (1967) for pipe conduits.

$$a = \left(\frac{K/\rho}{1 + (K/E)(D/e)C} \right)^{1/2} \quad (2)$$

where:

- c: correction for Poisson ratio effects
- D: inside diameter of the pipe
- e: pipe wall thickness
- E: Young's modulus of elasticity
- K: bulk modulus of elasticity of the fluid
- ρ : mass density of the fluid

The numerator (Equation 2) represents the sonic velocity in an infinite fluid. In the case of LOX the sonic velocity at saturated liquid conditions is about 2,900 ft/sec. This velocity may be reduced to 2,589 ft/sec in 6" diameter steel pipe, 2,500 ft/sec in 8" diameter steel pipe when the wall thickness is 1/10 inch and when the system is provided with expansion joints. For a 17" diameter pipe with 1/6 inch wall thickness, the sonic velocity is 2,410 ft/sec. This correction to

the wavespeed has been incorporated and calculated separately for each pipe in the theoretical model.

Another important parameter influencing the sonic velocity is the entrapped vapor. Gas bubbles dramatically reduce the pressure wave-speed (a) in a pipeline. With vapor present, the bulk modulus of elasticity is reduced, and is given by the following relationship:

$$K = \frac{K_{liq}}{1 + (V_g/V)(K_{liq}/K_g - 1)} \quad (3)$$

where:

$$\rho = \rho_g \frac{V_g}{V} + \rho_{liq} \frac{V_{liq}}{V}$$

$$V = V_{liq} + V_g$$

The subscript "g" refers to the gas (vapor) phase and "liq" to the liquid phase.

As little as 1% oxygen vapor (by volume) may reduce the sonic velocity by a factor 8.

The presence of vapor not only decreases the sonic velocity, but also reduces the effective amplitude of waterhammer pressure surges since the head rise is proportional to the sonic velocity.

These preliminary reflections give an insight on waterhammer concepts including the important parameters whose effects are discussed in subsequent chapters.

CHAPTER II

METHOD OF APPROACH

The starting point of this study was a computer code HYTRAN supplied by NASA/KSC, which can be used for calculating the pressure and velocity of a single-phase fluid in a piping system at designated locations during a transient. For initial conditions, the fluid is required to be in steady-state and all initial values of pressure and velocity need to be determined and used as input data. The project was composed of three major steps:

1. Familiarization with the HYTRAN program. This consisted of reviewing the computational methodology and basic modelling theory and input data calculation. The program was made operational on the NASA/KSC VAX 780 computer. As an initial test case, a sample input/output test case was provided with the HYTRAN User's Manual (Washburn) and was considered for one of the initial test cases. (The code supplied by NASA was a modified version of the initial program described in the User's Manual and some input data had to be recalculated. More details are given in Appendix B).
2. A first model of the LOX piping system was made. It was used to calculate the input data for the case of single-phase described by Lin, Moore, and Walker (1982). Since the computer time required for the execution of the program with

TABLE 1
MODEL FOR LOX PIPING SYSTEM

No. of pipe	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Pipe length (ft)	104.5	6.0	12.0	24.9	91.5	6.0	27.0	186.0	41.5	366.0	1082.5	7.0	6.0	6.0	6.0	6.0	6.0	6.0	18.8	9.7	27.0	37.0
Pipe diameter (in)	1.416	0.667	0.667	0.667	0.667	0.667	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.25	0.8	1.0	1.0	30.0
No. of junction	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	21
Elevation (ft)	222.4	125.3	123.4	119.6	94.7	88.0	88.0	85.0	85.0	43.5	13.0	10.7	14.0	14.0	14.0	14.0	14.0	11.0	11.0	16.2	16.2	53.2

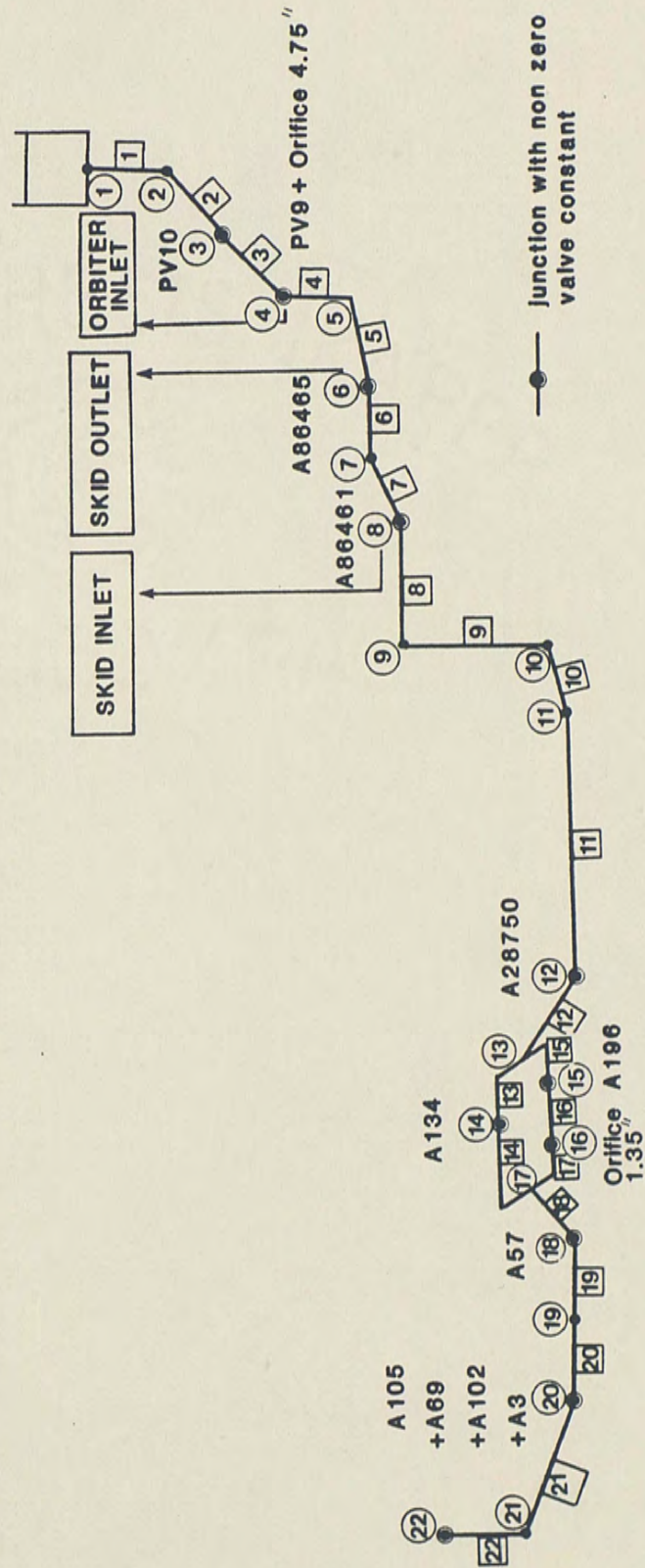


Fig. 3. Model for LOX Piping System.

this model was excessive, a simplified piping model was created as illustrated in Figure 3. The results with both models were similar and the second model was adopted during the remainder of the project. A sample HYTRAN input data calculation is found in Appendix E. A parametric study was conducted to obtain better understanding of the mechanism of wave propagation and to determine the most influencing variables. New boundary possibilities were added to HYTRAN in order to simulate satisfactorily a surge tank and lumped elements. The results are summarized in Appendix F.

3. For the two-phase flow test case (Lin, Moore, and Walker, 1982) extensive modifications in the computer program have been made (detail is found in Appendix C). A two-phase flow transient analysis is found in Appendix G, including the results. A classical steady state conditions approach is also presented in Appendix G.

Theory

The formation and propagation of pressure waves within a system result from complex hydraulic-system interactions.

The basic fluid mechanics equations, however, must be obeyed at each piping section in the system and at any time. Conservation of mass and momentum are two partial differential equations in terms of two dependent variables (velocity and head) and two independent variables (distance along the pipe and time).

Streeter and Wylie (1967) give a complete development of the basic equations which can also be found in Appendix A.

The governing transient equations for a single dimension (x) can be expressed as:

$$\text{Momentum: } g \frac{\partial H}{\partial x} + \frac{dV}{dt} + f \frac{V}{2D} = 0 \quad (4)$$

$$\text{Continuity: } \frac{a^2}{g} \frac{\partial V}{\partial x} + V \left(\frac{\partial H}{\partial x} + \sin \alpha \right) + \frac{\partial H}{\partial t} = 0 \quad (5)$$

The use of the method of characteristics converts the two partial differential equations into four ordinary differential equations which are put in finite-difference form and solved numerically. The method yields accurate results, easily handles a variety of boundary conditions and does not require excessive computer storage capacity.

The HYTRAN code uses the method of characteristics to numerically solve for pressure head and fluid velocity simultaneously. Various boundaries are incorporated (valves, reservoir, pump) and new ones have been added within this study. Appendix B presents a detailed description of the computer code HYTRAN and of its initial modifications from the original version.

Hytran Modifications

The modifications made to the HYTRAN program were an important part of this study. They made HYTRAN easier of use (input data), more versatile (new boundaries have been added) and, above all, offered the possibility of handling vapor cavity formation and collapse. The four

major changes detailed in Appendix C are presented in Table 2. The final version of HYTRAN is presented in Appendix H with a sample input and output data.

TABLE 2
MODIFICATIONS TO HYTRAN PROGRAM

MODIFICATION	REASON FOR MODIFICATION	EFFECT
1. C_{44} replaced by C_v (valve constants)	Simplify input data calculation Prevent errors	Time savings, less possibility of errors
2. Surge tank section replaced by new boundaries (includ- ing surge tank)	Error in original version Need of including new boundaries (lumped elements)	Larger capability of HYTRAN Better fit to experimental data
3. Gas/vapor cavity formation and collapse	Impossibility for the original version to handle the problem	Satisfying results
4. New output presentation	Need of including vapor cavity length to output data Capture the absolute pressure maximas occurring between two printouts	More effective and efficient data provision

CHAPTER III

RESULTS

Chapter II presented a model that may be used to assess the transient, two-phase pressure behavior within the NASA/KSC Liquid Oxygen Transport System. To validate or check the model, two operational draining scenarios, one single-phase and the other two-phase, were compared with model predictions.

Two sets of experimental data were provided by NASA (Lin, Moore, and Walker, 1982) including the drain scenarios corresponding to each case.

Single Phase Case

The first set is related to a drain sequence interruption caused by the closure of two valves in the storage tank area. The pressures were reported at three different points; viz:

1. skid inlet
2. skid outlet
3. orbiter inlet

The flow did not contain any vapor cavities and the analysis did not include two-phase considerations. A comparison of theoretical and experimental results are presented in Figures 4, 5, 6. For the steady state conditions, the agreement between predicted and measured data is very good. The timing is also satisfying (small delay which may be due

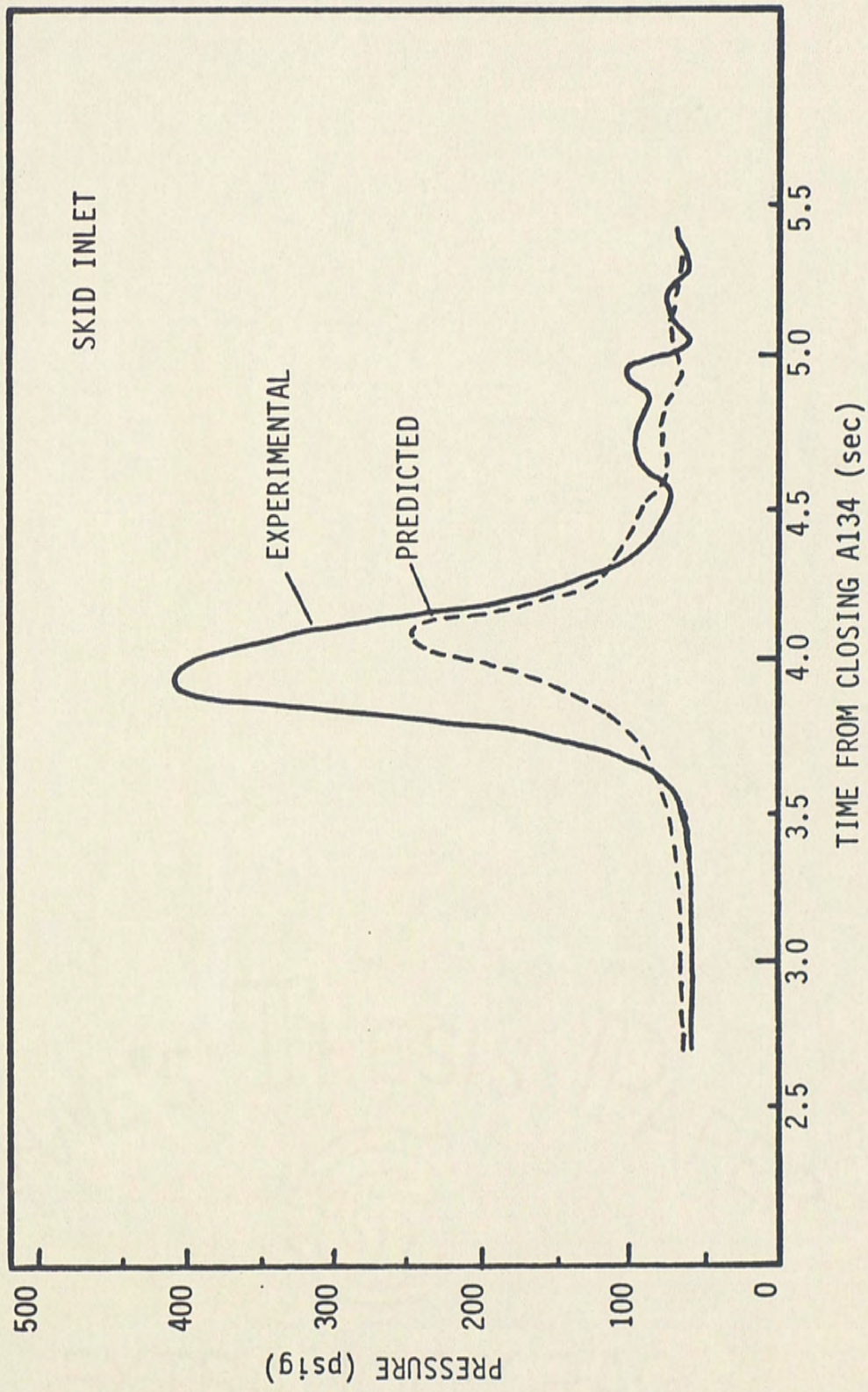


Fig. 4. Comparison with test data at the skid inlet for single-phase flow.

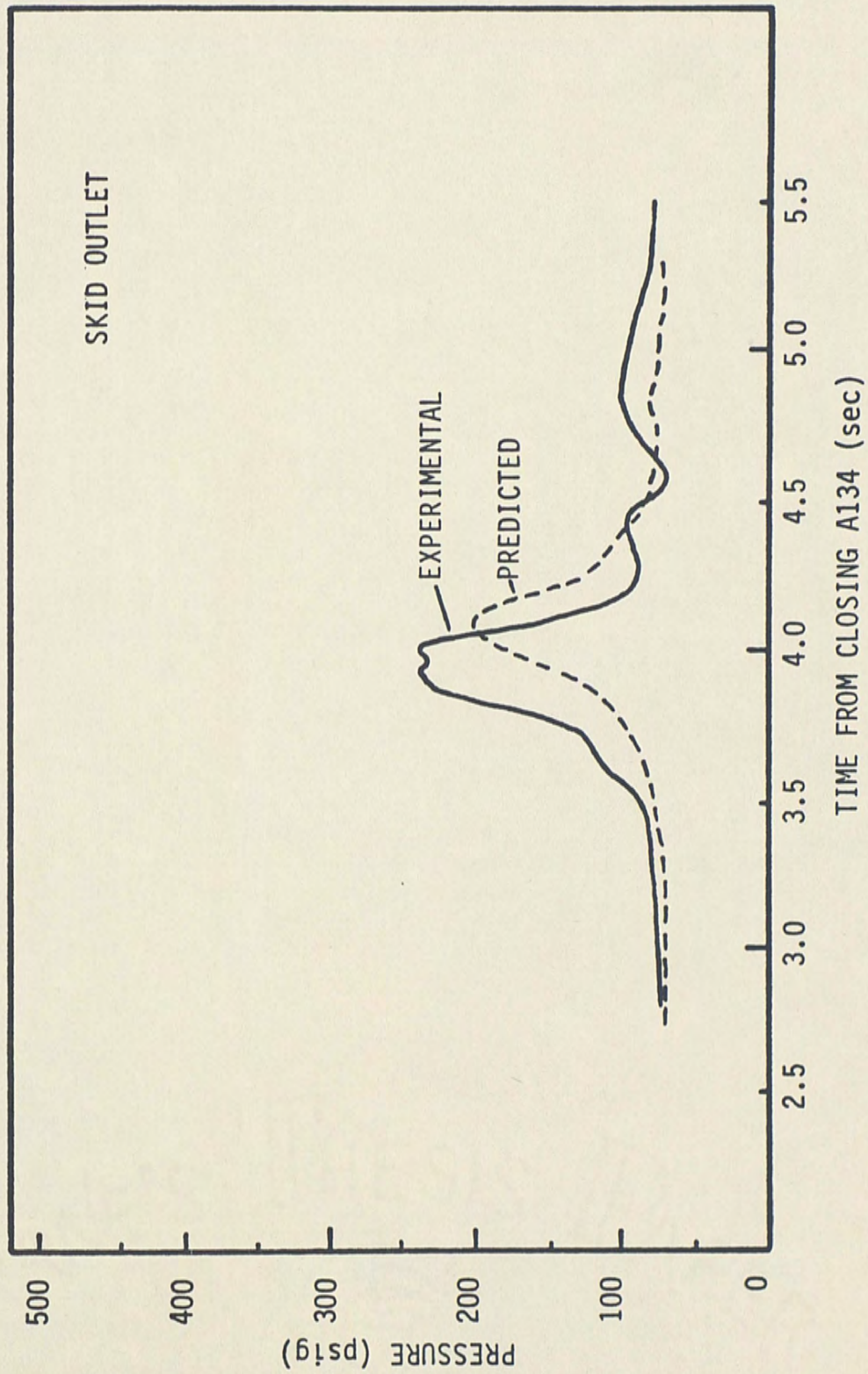


Fig. 5. Comparison with test data at the skid outlet for single-phase flow.

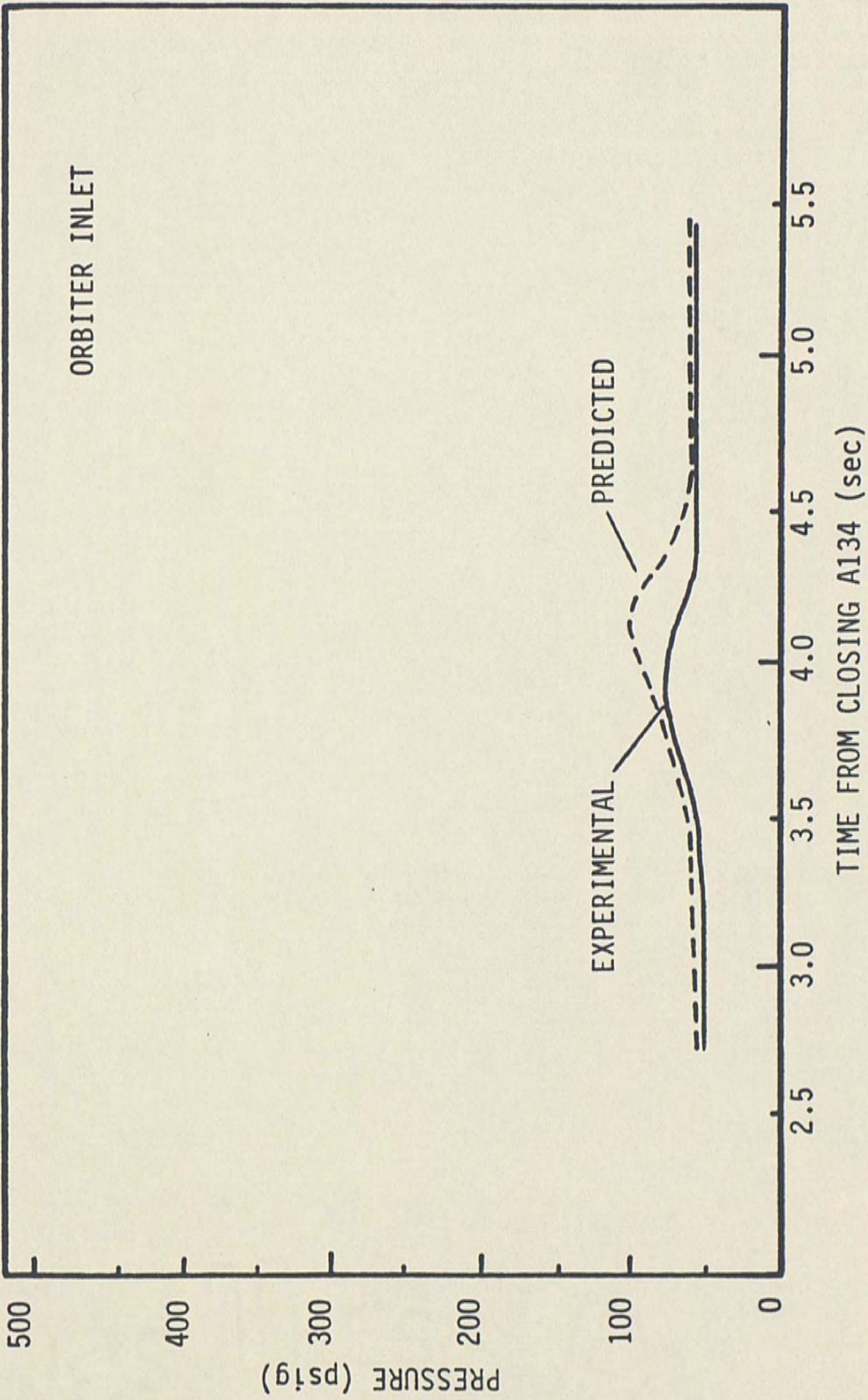


Fig. 6. Comparison with test data at the orbiter inlet for single-phase flow.

to a slightly too small sonic velocity in the cross-country section, to a smaller valve closure time, ...).

However the measured magnitude of the pressure spike at the skid inlet is 40% larger than the predicted peak pressure.

The predicted maximas at skid inlet and outlet are close together. This is due to the small distance separating the skid inlet from the skid outlet and the assumption of a discontinuity (for example the presence of a lumped inertia) may be able to simulate this behavior. Of particular interest is the filter which may behave in a more complex manner than a valve with equivalent C_v coefficient. Although unlikely, there may exist a vapor pocket or entrapped gas within the filter.

With the present possibilities offered by the program, the best representation of the system in the skid area would probably be the assumption of a lumped inertia at a junction located between the skid inlet and outlet in order to simulate the short horizontal pipe sections where the fluid may behave like a solid. Between skid outlet and orbiter inlet, the flexhose section (20 ft long) can be represented by a lumped capacitance with a given bulk modulus of elasticity much smaller than in the rest of the pipeline. Finally the TSM vent line may be modeled by a vapor chamber.

Two-Phase Flow Case

The pressure spike data with vapor cavity formation and collapse were obtained during a drain flow initiation on September 15, 1981. A description of the operations is given by Lin, Moore and Walker (1982).

Two sets of pressure spikes were measured: the first due to the collapse of the cavity located downstream from the valve PV10 and the second due to the collapse of the cavity located downstream the main fill valve. The first cavity resulted in complete backfilling of the pipeline and the second from a liquid column separation downstream the replenish valve which was held only 15% open. Since the origins of both pressure spikes are independent, they could be assessed separately. In this study only the second case was examined in detail.

As the replenish valve was positioned 15%, the liquid column downstream is subjected to less resistance than the upstream column at the replenish valve, hence, liquid column separation occurred. This situation lasted for over a hundred seconds until the main fill valve was eventually opened and the cavity backfilled. This whole process has been simulated, the details are given in Appendix G. A classical steady-state approach can also be found in Appendix G with the comparison of the results of both methods. An agreement within 5% was found concerning the steady state velocities of up-and-downstream columns, cavity length, and maximum pressure spike.

The comparison of the predicted pressure spikes with the experimental data are shown in Figures 7, 8, and 9. The following observations are made:

There is a difference in the timing; the predicted peaks occur "too early" and the theoretical time interval between the two peaks is smaller than the measured one. The results shown in Figures 7, 8, and 9 correspond to a nearly sharp edged orifice (at the orbiter inlet).

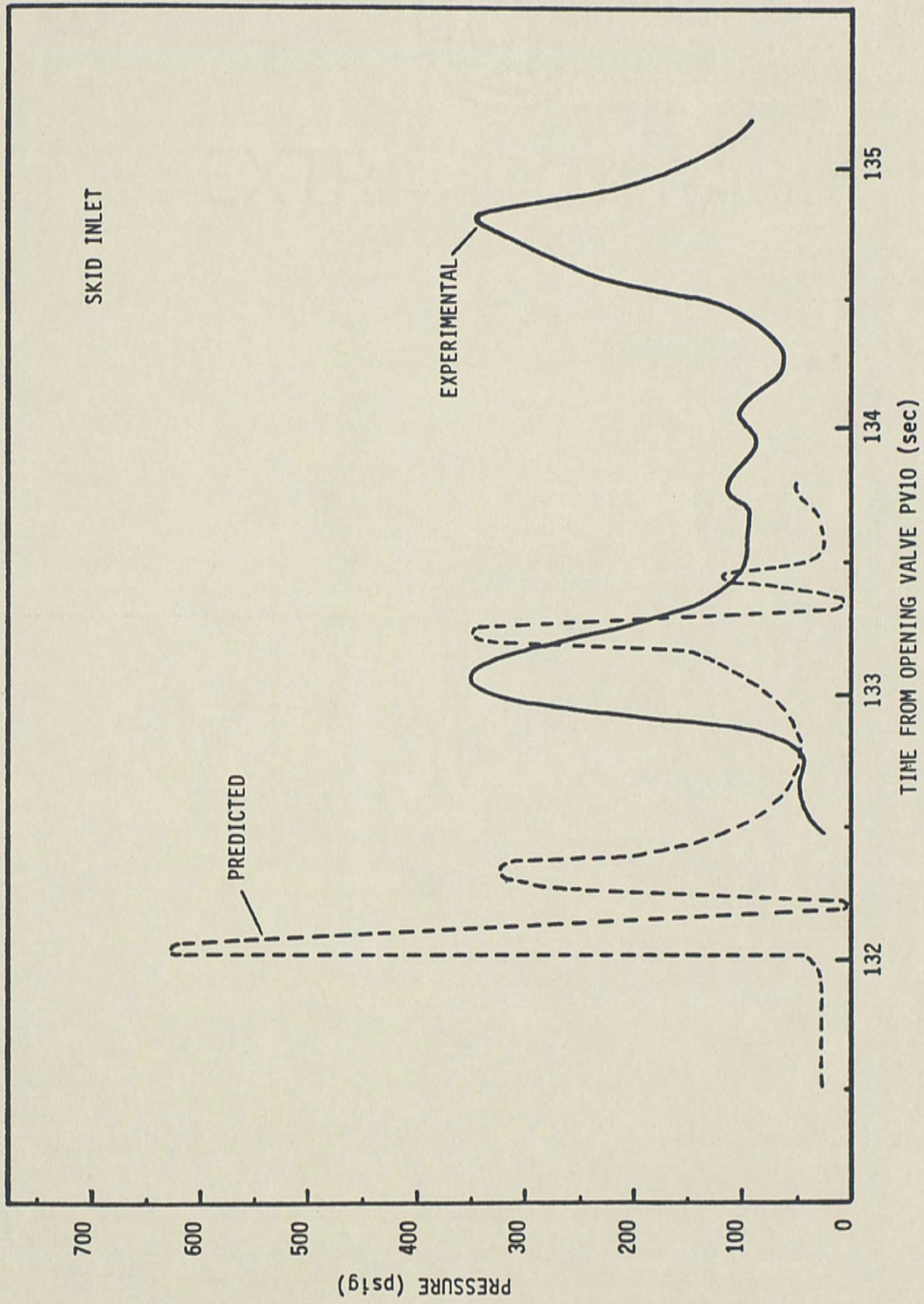


Fig. 7. Comparison with test data at the skid inlet for two-phase flow.

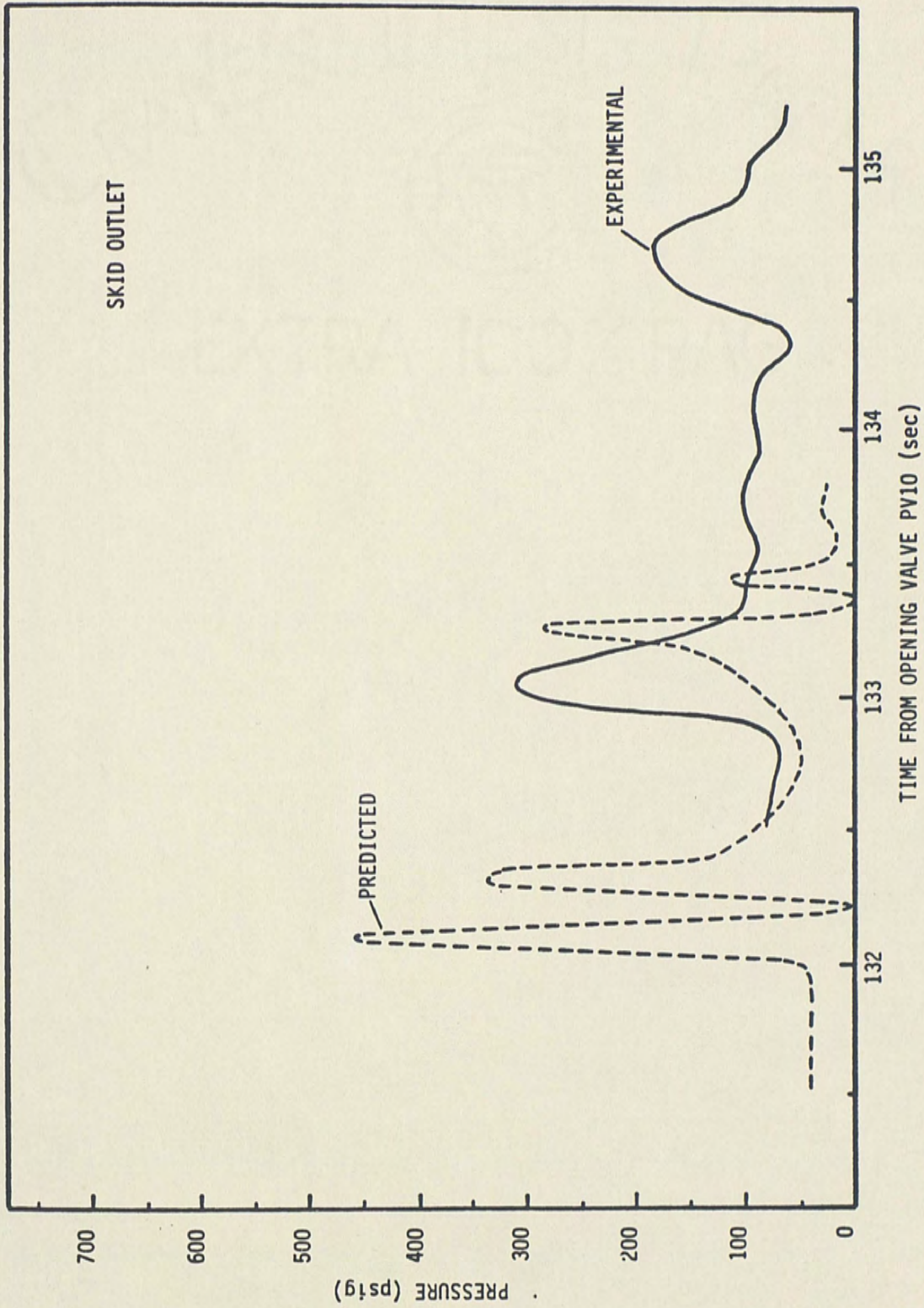


Fig. 8. Comparison with test data at the skid outlet for two-phase flow.

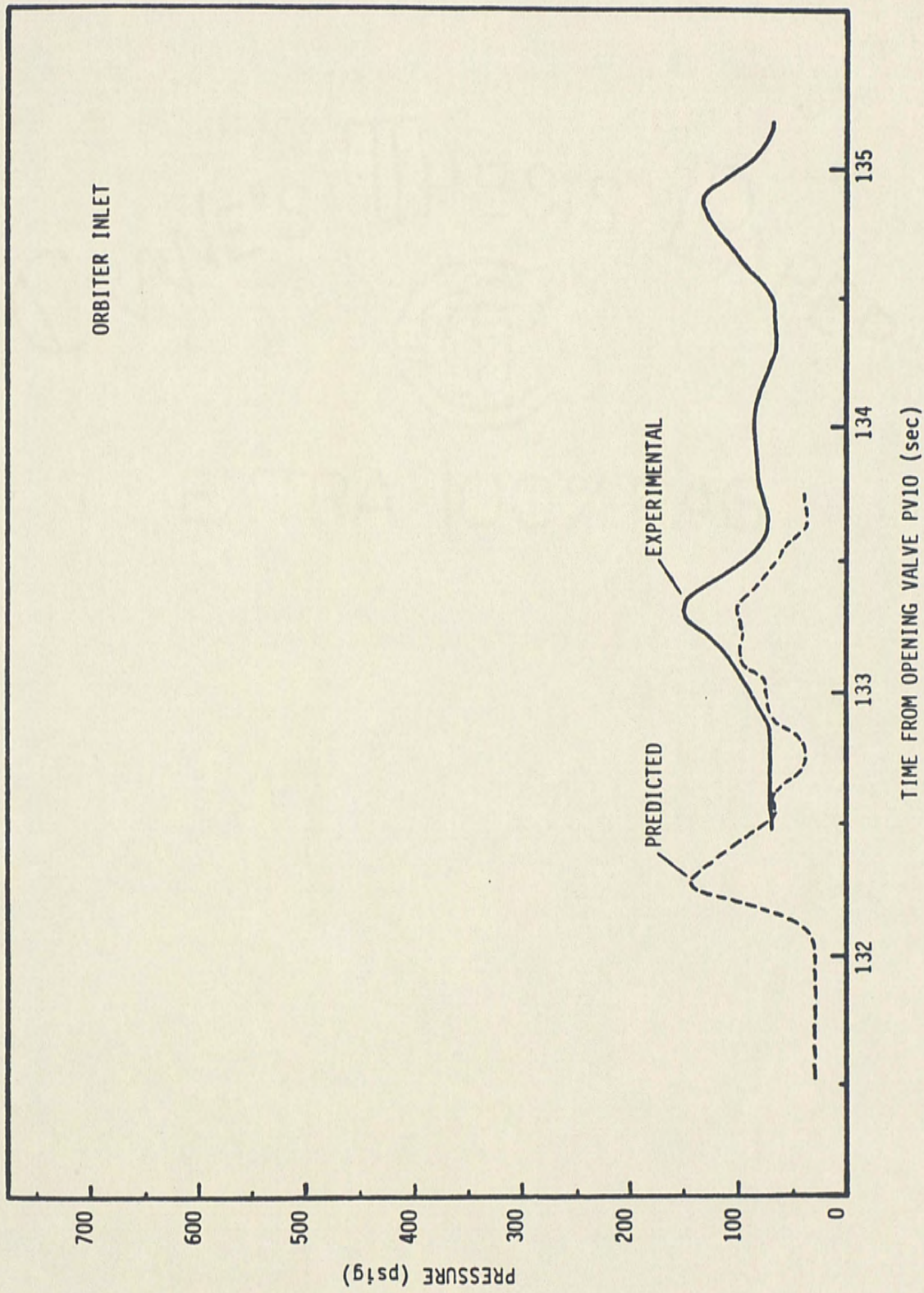


Fig. 9. Comparison with test data at the orbiter inlet for two-phase flow.

If the orifice is assumed to be a nozzle (change in C_v constant), the predicted peaks occur about 0.8 second earlier and the peak values are higher. This is due to the direct dependence of the column velocities on the valve constant and friction factors. In addition the size of the vapor cavity (over 180 feet) depends on the flow parameters. A larger cavity size yields a proportionally larger time delay for the first pressure spike.

The time interval between the first and second peak (which is the reflected wave at the storage area) is underestimated. The reason for this is the presence of vapor bubbles in the pipeline reducing drastically the sonic velocity as explained in Chapter 1. The presence of these small vapor cavities in the cross country line is confirmed by the output data. A possible improvement requires adjusting the sonic velocity in each pipe according to the two-phase void fraction (ratio of cavity length over pipelength).

At the skid inlet and outlet, the predicted maximum peak pressure is higher than in the experiment. Wylie and Streeter (1978) confirms that the model used overpredicts the pressure spikes and yields oscillations too large.

The results can be improved. In the model used, only the TSM vent line has been included but not the 20-feet-long flexhose. This elastic section can be simulated by a lumped capacitance at a junction which would level the oscillations. Another helpful change would be the already suggested sonic velocity adjustment to the vapor cavity fraction.

It can also be observed (Figure 7) that the curve representing the measured data may not truly describe the pressure variations. The recorded pressure data points are separated by a 0.1 second time interval. Any peak or low pressure occurring within this interval is not recorded. The measurement devices may have their own limitation including: inertia opposed to rapid pressure changes and limited pressure range (0 - 500 psi). These uncertainties yield conservative pressure readings which may underestimate and level the real pressure response.

In the case of the skid outlet and primarily the orbiter inlet, the amplitude of the predicted pressure peaks is in the range of the measured values.

An important observation is that if the replenish valve is held 100% open, no column separation should occur.

The pressure spikes due to the collapse of the vapor cavity at the ground side of the valve PV10 are simulated as a first approximation by creating artificially the cavity starting with a zero fluid velocity in the whole system and opening the valve A196 in the storage area (PV10 is kept closed). A vapor cavity is created downstream of PV10 and when the cavity reaches the desired size, the valve PV10 is opened, as shown by the valve's manufacture diagram (by giving it the corresponding values). The test was conducted starting the opening of PV10 after a cavity of 3 feet had been developed. The corresponding pressure spikes resulting from the collapse of that small cavity were too small in amplitude and occurred much earlier than the experimental

data showed (2 seconds difference). This tends to indicate that the actual cavity size is larger than 3-4 feet. An improved simulation of this set of pressure spikes should however include the TSM vent line as a real pipeline discharging to the atmosphere and containing various vapor chambers (since this line is not insulated and vapor pockets are therefore likely in the line). Besides its role as an air chamber this line did not have a large influence in the previous simulations because the valve A86483 had always been closed. However at the moment of registering pressure spikes due to the opening of PV10, the valve A86483 is still open and can discharge liquid into the dump basin. The presence of the TSM vent line acting like a pressure damper justifies the higher pressure at the orbiter inlet than at the skid outlet and inlet since the latter are located at the ground side of the TSM vent line junction.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

This study led to modifications of the computer program HYTRAN in order to broaden its field of application and make its use easier. Better results were obtained for the single-phase flow with the introduction of lumped capacitance and inertia. The large peak pressure drop between skid inlet and skid outlet may be simulated (at least partially) using both of these elements. The lumped capacitance models the flexhose and the lumped inertia models the horizontal pipe section between skid inlet and skid outlet.

Reasonable results were obtained in the case of the flow with vapor cavity collapse after having modified the subroutine PHASE designed to handle flow with vapor bubbles.

The differences between predicted and experimental results may have following origins:

1. Modification made in the piping system model.
2. Uncertainties on the system parameters (C_v valve coefficients are given for water at 60°F and may not be exactly the same for LOX. The E.T. is not cylindrical as assumed in the model).
3. Numerical errors due to interpolation (the choice of the timestep is very important for the case of long calculation time). The timestep is even more important in the case of a

flow with bubbles since in the subroutine PHASE the velocities at the grid points (method of characteristics, Appendix A) are not extrapolated.

4. The real valve opening curves may be different from the ideal curve used to simulate the opening or closure of the valves. There may also exist an uncertainty on the closure and/or opening time of the different valves.
5. The sonic velocity is an important parameter for which exact determination is still not well established for two-phase mixtures.
6. Eventually there are limitations with the model itself which is only a mathematical tool supposed to describe the real behavior of liquid flow. For example, the flow in a pipe cross section is not uniform as assumed in the model. Larger errors are introduced in the case of two-phase flow where the cavities probably move with the liquid, instead of remaining at the fixed locations.
7. Certain phenomena are still not completely understood. Although suggestions have been made in Chapter 3, the large peak pressure drop existing between the skid inlet and outlet is still not satisfactorily modeled. The filter may behave on a more complex way than an ordinary junction with a given constant C_V . Dynamic parameters affecting the rate of change in pressure and velocity may coexist with the traditional steady state constants.

8. Finally uncertainties in the readings (inertia of the pressure measure device) and discrete values introduce leveled pressure spikes.

The following recommendations for future work are made:

1. For the single-phase flow there are still various possible combinations of newly introduced devices (lumped inertia, capacitance, surge tank and air chamber) to be included in the model.
2. For the two-phase flow the sonic velocity should be recalculated at each timestep for each pipe using the void fraction

$$X(J) = \frac{V_g}{V} = \frac{CAVL(J)}{XL(J)}$$

in pipe J in equation (3) (Chapter 1) which yield

$$a = a_{liq} \left(\frac{\rho_{liq}}{(\rho_g X(J) + \rho_{liq} (1 - X(J))(1 + X(J)) \left(\frac{a_{liq}^2 \rho_{liq}}{a_g^2 \rho_g} - 1 \right))} \right)^{\frac{1}{2}}$$

where a_{liq} and a_g are the sonic velocities in liquid and gas, respectively in ft/s and ρ_{liq} and ρ_g are the weight densities (lb/ft³).

3. In order to limit the large oscillations occurring with vapor cavity collapse, an adequate correction factor should be incorporated to the sonic velocity to take into account the dependence of the sonic velocity with the pressure in the

case of cavity collapse. Equation (1) (Chapter 1) should be formulated as follows:

$$\Delta H = \frac{a(P)}{g} \Delta V \quad \text{where "a" is pressure dependent}$$

This modification would affect the rate of pressure change, namely: the reduced slope of the pressure versus time curve.

4. A major modification could be the adaptation to HYTRAN of the Specified Time Intervals Method with Interpolation developed in Wylie and Streeter (1978) where the theory and the computer program can be found.
5. Investigate the effect of non-condensable gases (Helium, Nitrogen) by considering the gas cavities as chambers located at the piping sections.
6. Use the liquid hydrogen experimental data as additional test cases.
7. Introduce additional measurement devices in the skid region (i.e., upstream and downstream of the filter) to facilitate a more detailed analysis of the large pressure drop.
8. Apply the model to the Vandenberg Air Force Base LOX system.

APPENDIX A

TRANSIENT FLOW EQUATIONS

Derivation of Basic Equations

Equation of motion

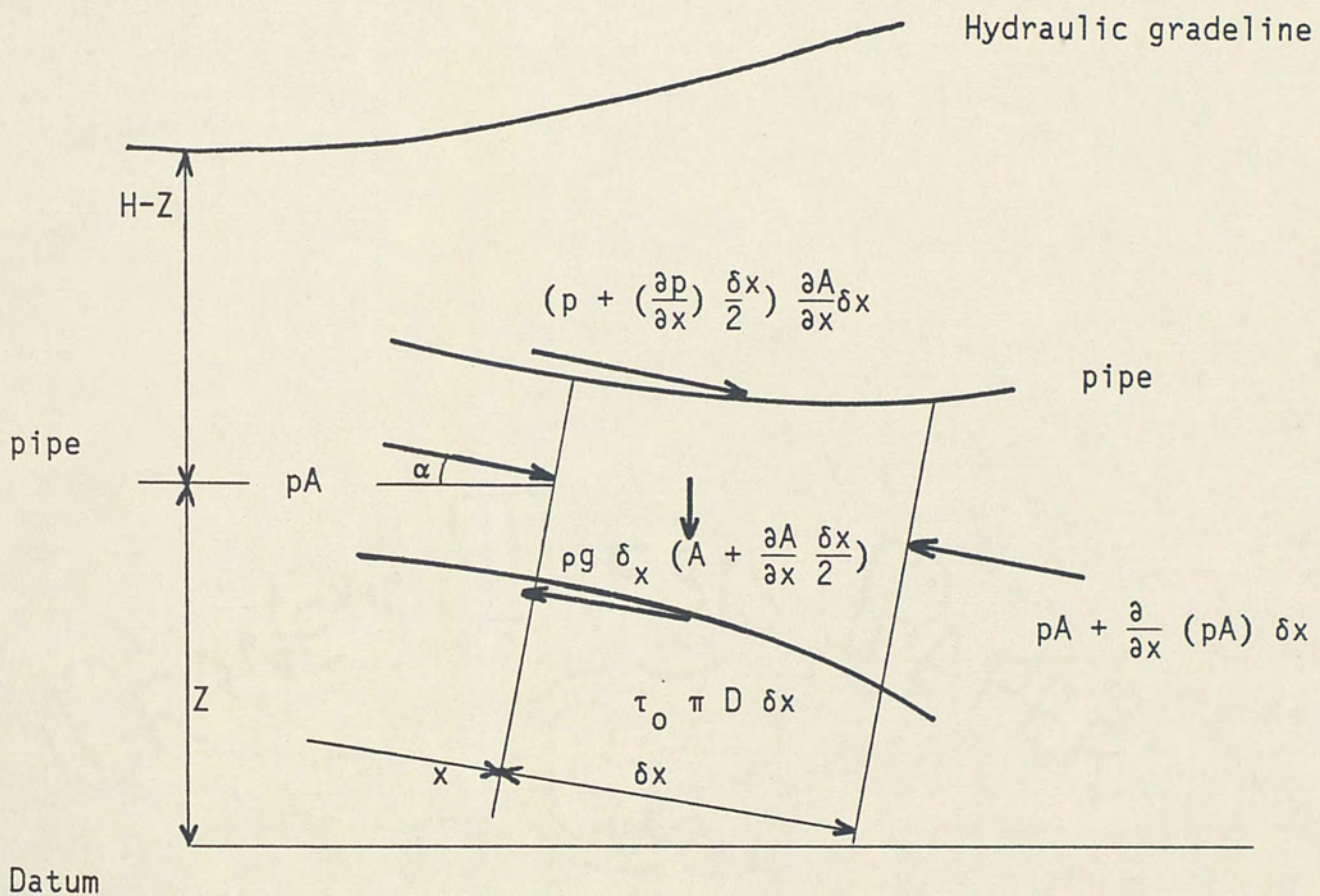


Fig. 10. Forces on free body of fluid in a conduit.

The pressure is assured constant over any section of the conduit.

Summing all the forces yields

$$pA - (pA + \frac{\partial}{\partial x} (pA) \delta x) + (p + \frac{\partial p}{\partial x} \frac{\delta x}{2}) \frac{\partial A}{\partial x} \delta x + \rho g \delta x (A + \frac{\partial A}{\partial x} \frac{\delta x}{2}) \sin \alpha - \tau_o \pi D \delta x = \rho (A + \frac{\partial A}{\partial x} \frac{\delta x}{2}) \delta x \frac{dV}{dt}$$

Dropping the second order terms

$$- \frac{\partial p}{\partial x} A \delta x - p \frac{\partial A}{\partial x} \delta x + p \frac{\partial A}{\partial x} \delta x + \rho g A \sin \alpha \delta x - \tau_0 \pi D \delta x = \rho A \frac{dV}{dt} \delta x$$

$$\text{or } \frac{1}{\rho} \frac{\partial p}{\partial x} - g \sin \alpha + \frac{\tau_0 \pi D}{A \rho} + \frac{dV}{dt} = 0$$

Assuming ρ independent of H yields

$$p = \rho g (H - Z)$$

$$\bullet \quad \frac{\partial p}{\partial x} = \rho g \left(\frac{\partial H}{\partial x} - \frac{\partial Z}{\partial x} \right) = \rho g \left(\frac{\partial H}{\partial x} + \sin \alpha \right)$$

$$\bullet \quad A = \frac{\pi D^2}{4}$$

The shear stress τ_0 at the wall of the conduit is taken to be the steady-state shear stress.

$$\bullet \quad \tau_0 = \frac{\rho f V}{8} \quad \text{where } f \text{ is the Darcy Weisback friction factor}$$

$$\text{Finally } \frac{\rho g \left(\frac{\partial H}{\partial x} + \sin \alpha \right)}{\rho} - g \sin \alpha + \frac{\pi D}{\pi D^2 \rho} (4) \frac{\rho f V^2}{8} + \frac{dV}{dt} = 0$$

$$\text{or } g \frac{\partial H}{\partial x} + \frac{dV}{dt} + \frac{f V |V|}{2D} = 0 \quad (4)$$

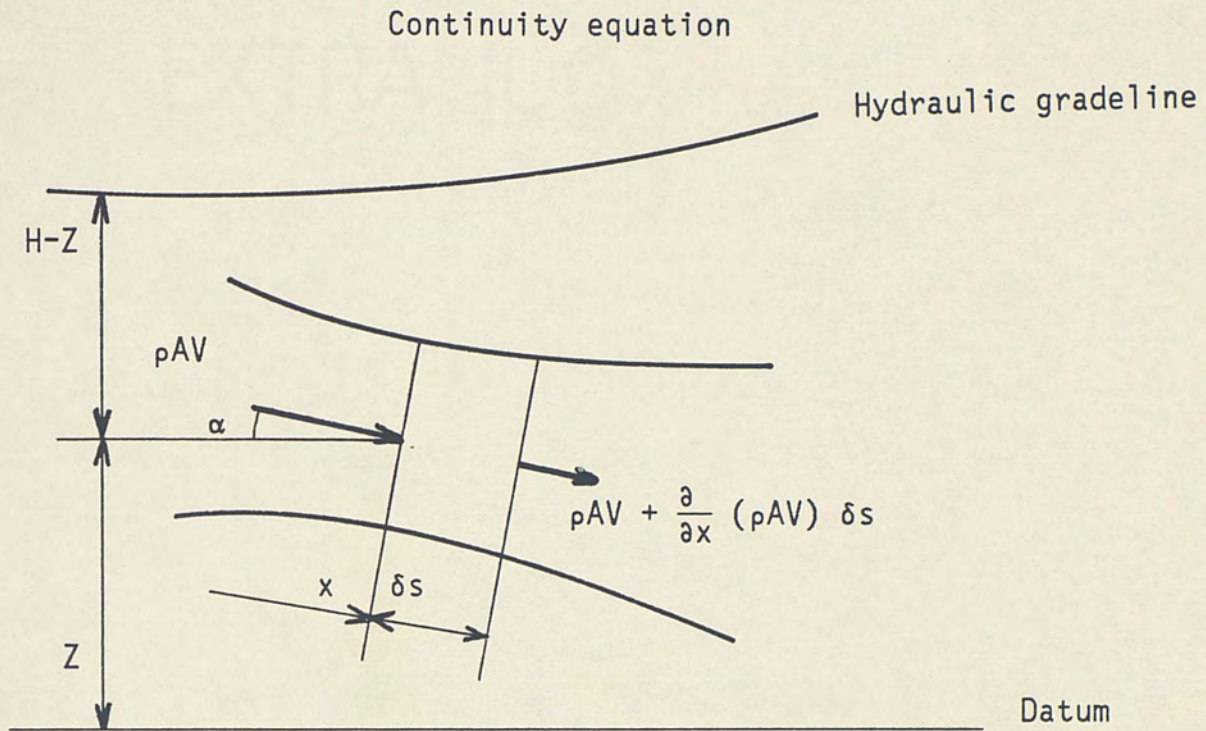


Fig. 11. Continuity equation.

$$\rho AV - \left(\rho AV + \frac{\partial}{\partial x} (\rho AV) \delta s \right) = \frac{\partial}{\partial t} (\rho A \delta s)$$

$$\rightarrow \left(- \frac{\partial \rho}{\partial x} AV - \rho \frac{\partial A}{\partial x} V - \rho A \frac{\partial V}{\partial x} \right) \delta s = \frac{\partial \rho}{\partial t} A \delta s + \rho \frac{\partial A}{\partial t} \delta s + \rho A \frac{\partial}{\partial t} (\delta s)$$

$$\rightarrow \frac{V}{\rho} \frac{\partial \rho}{\partial x} + \frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{V}{A} \frac{\partial A}{\partial x} + \frac{1}{A} \frac{\partial A}{\partial t} + \frac{1}{\delta s} \frac{\partial}{\partial t} (\delta s) + \frac{\partial V}{\partial x} = 0$$

But also $\frac{d\rho}{dt} = V \frac{\partial \rho}{\partial x} + \frac{\partial \rho}{\partial t}$ (total derivatives following the motion of the fluid)

$$\frac{dA}{dt} = V \frac{\partial A}{\partial x} + \frac{\partial A}{\partial t}$$

$$\frac{d}{dt} \delta s = V \frac{\partial \delta s}{\partial x} + \frac{\partial \delta s}{\partial t} = \frac{\partial \delta s}{\partial t} \quad \text{since } \delta s \text{ is only dependent on } t.$$

$$\rightarrow \frac{1}{\rho} \frac{dp}{dt} + \frac{1}{A} \frac{dA}{dt} + \frac{1}{\delta s} \frac{d\delta s}{dt} + \frac{\partial V}{\partial x} = 0$$

The bulk modulus of elasticity of the liquid is defined as

$$K = \frac{\frac{dp}{dt}}{\frac{1}{\rho} \frac{dp}{dt}}$$

$$\rightarrow \frac{1}{\rho} \frac{dp}{dt} = \frac{1}{K} \frac{dp}{dt}$$

Using Poisson's ratio yields the time rate of increase of radius.

$$\rightarrow \frac{1}{A} \frac{dA}{dt} = \frac{2}{E} \left(\frac{d\sigma_2}{dt} - \mu \frac{d\sigma_1}{dt} \right)$$

$$\rightarrow \frac{1}{\delta s} \frac{d\delta s}{dt} = \frac{1}{E} \left(\frac{d\sigma_1}{dt} - \mu \frac{d\sigma_2}{dt} \right)$$

Combining yields

$$\frac{\partial V}{\partial x} + \frac{1}{K} \frac{dp}{dt} + \frac{1}{E} \left(\frac{d\sigma_2}{dt} (2 - \mu) + \frac{d\sigma_1}{dt} (1 - 2\mu) \right) = 0$$

The circumferential stress rate is $\frac{d\sigma_2}{dt} = \left(\frac{dp}{dt} \right) \frac{D}{2e}$

For a pipe supported at the upstream end only $\frac{d\sigma_1}{dt} = \left(\frac{dp}{dt} \right) \frac{D}{4e}$

$$\rightarrow \frac{\partial V}{\partial x} + \frac{1}{K} \frac{dp}{dt} \left(1 + \frac{KD}{Ee} C_1 \right) = 0 \quad \underline{C_1 = \frac{5}{4} - \mu}$$

Defining $a = \frac{(K/\rho)^{\frac{1}{2}}}{(1 + (K/E) (D/e) C_1)^{\frac{1}{2}}}$ following expression is obtained:

$$\rightarrow \frac{\partial V}{\partial x} + \frac{1}{\rho a^2} \frac{dp}{dt} = 0$$

$$\text{But } \frac{dp}{dt} = V \frac{\partial p}{\partial x} + \frac{\partial p}{\partial t} = V \rho g \left(\frac{\partial H}{\partial x} + \sin \alpha \right) + \rho g \frac{\partial H}{\partial t}$$

Therefore:

$$\frac{a^2}{g} \frac{\partial V}{\partial x} + V \left(\frac{\partial H}{\partial x} + \sin \alpha \right) + \frac{\partial H}{\partial t} = 0 \quad (5)$$

which is the continuity equation for pipe having small deformation.

NOTE: • When the pipe is anchored throughout against axial movement

$$\frac{d\sigma_1}{dt} = \mu \frac{d\sigma_2}{dt} \quad \text{and} \quad C_1 = 1 - \mu^2$$

•• When there are expansion joints throughout the piping system:

$$\frac{d\sigma_1}{dt} = 0 \quad \text{so} \quad C_1 = 1$$

There is only an influence on the sonic velocity a .

Method of Characteristics

Equation of motion (4) yields

$$g \frac{\partial H}{\partial x} + \frac{dV}{dt} + \frac{fV}{2D} |V| = 0 \rightarrow L_1 = g \frac{\partial H}{\partial x} + V \frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + f \frac{V}{2D} |V| = 0$$

Continuity equation (5) yields

$$\frac{a^2}{g} \frac{\partial V}{\partial x} + V \left(\frac{\partial H}{\partial x} + \sin \alpha \right) + \frac{\partial H}{\partial t} = 0 \rightarrow L_2 = \frac{\partial H}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} + V \frac{\partial H}{\partial x} + V \sin \alpha = 0$$

General characteristics method. Define χ such that

$$L_1 + \chi L_2 = \chi \left(\frac{\partial H}{\partial x} \left(V + \frac{g}{\chi} \right) + \frac{\partial H}{\partial t} \right) + \left(\frac{\partial V}{\partial x} \left(V + \frac{a^2}{g} \chi \right) + \frac{\partial V}{\partial t} \right) + \chi V \sin \alpha + \frac{fV}{2D} |V| = 0 \quad (6)$$

$$\text{if } \frac{dx}{dt} = V + \frac{g}{\chi} = V + \frac{a^2}{g} \chi \quad (6) \text{ becomes}$$

$$\chi \frac{dH}{dt} + \frac{dV}{dt} + \chi V \sin \alpha + f \frac{V |V|}{2D} = 0 \quad (7)$$

In this case $\chi = \pm \frac{g}{a}$ and $\frac{dx}{dt} = V \pm a$.

The two characteristic equations corresponding to (7) are then

for $\chi = \frac{g}{a}$	C^+	$\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{g}{a} V \sin \alpha + f \frac{V V }{2D} = 0$ $\frac{dx}{dt} = V + a$
for $\chi = \frac{-g}{a}$	C^-	$\frac{-g}{a} \frac{dH}{dt} + \frac{dV}{dt} - \frac{g}{a} V \sin \alpha + f \frac{V V }{2D} = 0$ $\frac{dx}{dt} = V - a$

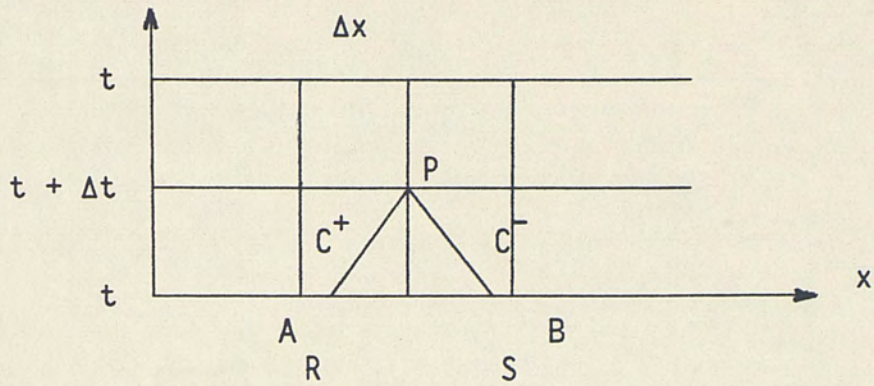


Fig. 12. Grid lines for method of specified time intervals.

In finite difference form C^+ and C^- become

$$C^+ \quad \begin{aligned} V_P - V_R + \frac{g}{a} (H_P - H_R) + \frac{g}{a} V_R \sin \alpha (t_P - t_R) + \frac{f}{2D} V_R |V_R| (t_P - t_R) &= 0 \\ x_P - x_R &= (V_R + a) (t_P - t_R) \end{aligned}$$

$$C^- \quad \begin{aligned} V_P - V_S - \frac{g}{a} (H_P - H_S) - \frac{g}{a} V_S \sin \alpha (t_P - t_S) + \frac{f}{2D} V_S |V_S| (t_P - t_S) &= 0 \\ x_P - x_S &= (V_S - a) (t_P - t_S) \end{aligned}$$

With the conditions known at A, B, C they can be evaluated at R and S by linear interpolation

$$\frac{x_C - x_R}{x_C - x_A} = \frac{V_C - V_R}{V_C - V_A} \quad \text{where} \quad \begin{aligned} x_P &= x_C \\ x_C - x_A &= \Delta x \end{aligned}$$

$$V_R = \frac{V_C - \theta a (V_C - V_A)}{1 + \theta (V_C - V_A)}$$

$$V_S = \frac{V_C - \theta a (V_C - V_B)}{1 - \theta (V_C - V_B)}$$

$$H_R = H_C - \theta (V_R + a) (H_C - H_A)$$

$$\text{where } \theta = \frac{\Delta t}{\Delta x}$$

$$H_S = H_C + \theta (V_S - a) (H_C - H_B)$$

The derivation is given in Addendum 1 at the end of this Appendix.

Finally:

$$V_P = 0.5 (V_R + V_S + \frac{g}{a} (H_R - H_S) - \frac{g}{a} \Delta t \sin \alpha (V_R - V_S)$$

$$- f \frac{\Delta t}{2D} (V_R |V_R| + V_S |V_S|))$$

$$H_P = 0.5 (H_R + H_S + \frac{a}{g} (V_R - V_S) - \Delta t \sin \alpha (V_R + V_S)$$

$$- \frac{a}{g} f \frac{\Delta t}{2D} (V_R |V_R| - V_S |V_S|))$$

which are considered valid for any interior point (in a pipe).

Boundary conditions

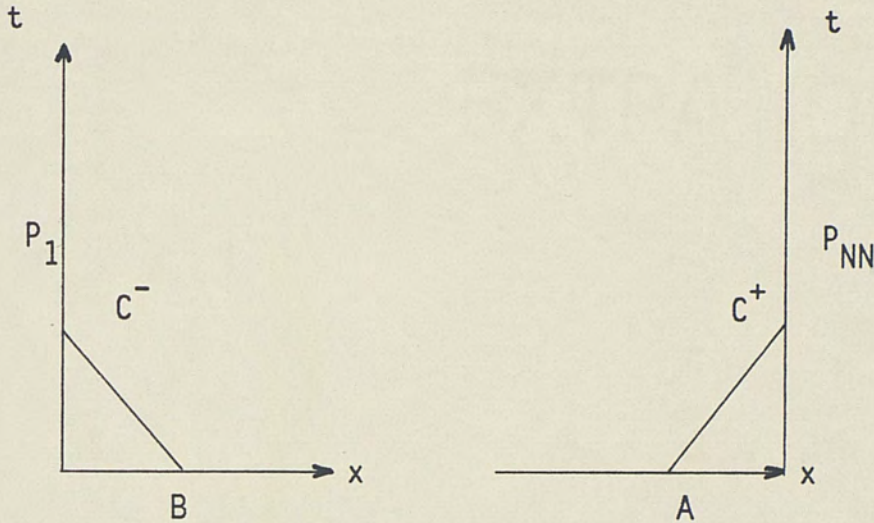


Fig. 13. Characteristics at the boundaries.

At the end of the pipe only one characteristic equation is available. For a left-end boundary (C^-) holds, for a right-hand boundary (C^+) holds.

At each end there is thus one equation for the two unknowns V_p and H_p .

Another equation is V_p and/or H_p is necessary. It is given by the boundary itself.

- For an upstream end C^- becomes

$$V_{P,1} = V_S + \frac{g}{a} (H_{P,1} - H_S) + \frac{g}{a} \Delta t V_S \sin \alpha - \frac{f}{2D} \Delta t V_S |V_S|$$

$$\text{or } \underline{V_{P,1} = C_1 + C_2 H_{P,1}} \quad (8)$$

where $C_2 = \frac{g}{a}$ and C_1 is only dependent of known values.

$$C_1 = V_S \left(1 + C_2 \Delta t \sin \alpha - \frac{f \Delta t}{2D} |V_S| \right) - C_2 H_S$$

- For a downstream and C_+ becomes

$$V_{P,NN} = V_R - \frac{g}{a} (H_{P,NN} - H_R) - \frac{g}{a} V_R \Delta t \sin \alpha - \frac{f}{2D} \Delta t V_R |V_R|$$

or $V_{P,NN} = C_3 - C_2 H_{P,NN}$

where $C_3 = V_R \left(1 - C_2 \Delta t \sin \alpha - \frac{f \Delta t}{2D} |V_R| \right) + C_2 H_R$

Auxiliary equations

Reservoir at fixed level at upstream end:

$$H_{P,1} = H_0$$

$$V_{P,1} = C_1 + C_2 H_{P,1} \quad (9)$$

Reservoir at fixed level at downstream end:

$$H_{P,NN} = H_0$$

→ $H_{P,NN}$ and $V_{P,NN}$.

$$V_{P,NN} = C_3 - C_2 H_{P,NN}$$

Series connection:

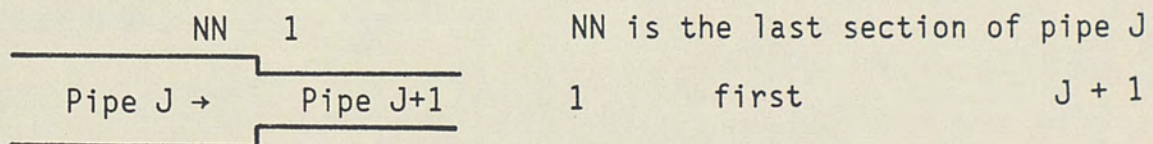


Fig. 14. Pipes connected in series.

$$V_{P,J,NN} A_J = V_{P,J+1,1} A_{J+1} \quad A: \text{ pipe cross sectional area}$$

$$H_{P,J,NN} = H_{P,J+1,1}$$

But also holds

$$V_{P,J,NN} = C_3 - C_{2,J} H_{P,J,NN} \quad (10)$$

$$V_{P,J+1,1} = C_1 + C_{2,J+1} H_{P,J+1,1} \quad (11)$$

Solving these equations simultaneously yields (see addendum 2 at the end of this appendix)

$$H_{P,J+1,1} = H_{P,J,NN} = \frac{-C_1 A_{J+1} + C_3 A_J}{C_{2,J+1} A_{J+1} + C_{2,J} A_J}$$

$$V_{P,J,NN} = C_3 - C_{2,J} H_{P,J,NN}$$

$$V_{P,J+1,1} = C_1 + C_{2,J+1} H_{P,J+1,1}$$

Valve or orifice in the interior of a pipeline:

$$* \quad V_{P,J,NN} A = C_d A_G (2g H_{P,J,NN} - H_{P,J+1,1})^{\frac{1}{2}}$$

A: pipe cross sect area

A_G : valve area opening

C_d : valve discharge coefficient.

Defining $\tau = \frac{C_d A_G}{(C_d A_G)_o}$ as the dimensionless valve opening
 ("o" refers to steady-state conditions).

$$* \quad V_{oJ} A = (C_d A_G)_o (2g\Delta H_o)^{\frac{1}{2}} \quad \text{in steady-state conditions}$$

$$\frac{V_{P,J,NN}}{V_{oJ}} = \tau \frac{(H_{P,J,N} - H_{P,J+1,1})^{\frac{1}{2}}}{(\Delta H_o)^{\frac{1}{2}}}$$

Also holds $V_{P,J,NN} = C_3 - C_2 H_{P,J,NN}$

and $V_{P,J+1,1} = C_1 + C_2 H_{P,J+1,1}$

and $V_{P,J,N} = V_{P,J+1,1}$

The solution derived in addendum 3 (end of Appendix A) is

$$V_{P,J,NN} = V_{P,J+1,1} = -C_4 + (C_4^2 + C_4 (C_1 + C_3))^{\frac{1}{2}}$$

where $C_4 = \frac{\tau^2 V_{oJ}^2}{\Delta H_o C_2}$

Valve or orifice at the end of pipe:

Now ΔH_o becomes H_o across the valve

$$\frac{V_{P,NN}}{V_o} = \tau \left(\frac{H_{P,NN}}{H_o} \right)^{\frac{1}{2}} \quad \tau = \frac{C_d A_G}{(C_d A_G)_o}$$

and
$$V_{P,NN} = C_3 - C_2 H_{P,NN}$$

Solving for $V_{P,NN}$ yields (see addendum 4 at the end of this Appendix)

$$V_{P,NN} = -\frac{C_4^1}{2} + \left(\left(\frac{C_4^1}{2} \right)^2 + C_3 C_4^1 \right)^{\frac{1}{2}}$$

where
$$C_4^1 = \frac{\tau^2 V_o^2}{H_o C_2}$$

In conclusion, knowing the heads and velocities at some steady-state conditions at time "t," this method allows the determination of the new values of V_p and H_p at all the sections at time "t + Δt " and so on for any transient phenomena (valve opening or closure). HYTRAN fundamental equations written in FORTRAN are derived in Addendum 5.

ADDENDUM 1

a) Derivation of $V_R = \frac{V_C - a\theta (V_C - V_A)}{1 + \theta (V_C - V_A)}$

Given • $\frac{x_C - x_R}{x_C - x_A} = \frac{V_C - V_R}{V_C - V_A}$ (12)

• $x_P - x_R = (V_R + a) (t_P - t_R)$ (13)

• $x_P = x_C$ (14)

• $x_C - x_A = \Delta x$ (15)

• $t_P - t_R = \Delta t$ (16)

• $\theta = \frac{\Delta t}{\Delta x}$ (17)

Combining (12), (14), (15) yields

$$\frac{V_C - V_R}{V_C - V_A} = \frac{x_P - x_R}{\Delta x}$$

Using (13), (16), and (17)

$$\frac{V_C - V_R}{V_C - V_A} = (V_R + a) \frac{\Delta t}{\Delta x} = (V_R + a) \theta$$

or

$$V_R = \frac{V_C - a\theta (V_C - V_A)}{1 + \theta (V_C - V_A)}$$

b) Derivation of $V_S = \frac{V_C - \theta a (V_C - V_B)}{1 + \theta a (V_C - V_B)}$

Given • $\frac{x_C - x_S}{x_C - x_B} = \frac{V_C - V_S}{V_C - V_B}$

• $x_P - x_S = (V_S - a) (t_P - t_S)$

• $x_P = x_C$

• $x_B - x_C = \Delta x$

• $t_P - t_S = \Delta t$

• $\theta = \frac{\Delta t}{\Delta x}$

Again we perform the same substitutions as above and get

$$\frac{V_C - V_S}{V_C - V_B} = (V_S - a) \frac{(t_P - t_S)}{(x_C - x_B)} = (V_S - a) \frac{\Delta t}{(-\Delta x)} = -(V_S - a) \theta$$

Solving for V_S yields

$$V_S \left(-\theta + \frac{1}{V_C - V_B} \right) = \frac{V_C}{V_C - V_B} - a\theta$$

or

$$V_S = \frac{V_C - \theta a (V_C - V_B)}{1 - \theta (V_C - V_B)}$$

c) Derivation of $H_R = H_C - \theta (V_R + a) (H_C - H_A)$

Given • $\frac{x_C - x_R}{x_C - x_A} = \frac{H_C - H_R}{H_C - H_A}$

• $x_P - x_R = (V_R - a) (t_P - t_R)$

• $x_P = x_C$

• $\frac{t_P - t_R}{x_C - x_A} = \theta$

$$\frac{H_C - H_R}{H_C - H_A} = \frac{x_P - x_R}{x_C - x_A} = (V_R + a) \theta$$

Directly we get

$$H_R = H_C - \theta (V_R + a) (H_C - H_A)$$

d) Derivation of $H_S = H_C + \theta(V_S - a) (H_C - H_A)$

Given • $\frac{x_C - x_S}{x_C - x_B} = \frac{H_C - H_S}{H_C - H_B}$

• $x_P - x_S = (V_S - a) (t_P - t_S)$

• $x_P = x_C$

• $\frac{t_P - t_S}{x_B - x_C} = \theta$

$$\frac{H_C - H_S}{H_C - H_B} = \frac{x_P - x_S}{x_C - x_B} - (V_S - a) \theta$$

And so

$$H_S = H_C + \theta(V_S - a) (H_C - H_S).$$

ADDENDUM 2

Derivation of $H_{P,J+1,1} = H_{P,J,NN} = \frac{-C_1 A_{J+1} + C_3 A_J}{C_{2,J+1} A_{J+1} + C_{2,J} A_J}$

Given • $V_{P,J,NN} = C_3 - C_{2,J} H_{P,J,NN}$ (18)

• $V_{P,J+1,1} = C_1 + C_{2,J+1} H_{P,J+1,1}$ (19)

• $V_{P,J,NN} A_J = V_{P,J+1,1} A_{J+1}$ (20)

• $H_{P,J,NN} = H_{P,J+1,1}$ (21)

Solving for $H_{P,J,NN}$ and $H_{P,J+1,1}$ in (18) and (19) and substituting into (21) yields

$$C_{2,J+1} V_{P,J,NN} + C_{2,J} V_{P,J+1,1} = C_3 C_{2,J+1} + C_1 C_{2,J}$$

From (20) $V_{P,J,NN}$ is obtained as following

$$V_{P,J,NN} = \frac{V_{P,J+1,1} A_{J+1}}{A_J}$$

Substitution back into the previous equation yields

$$V_{P,J+1,1} (C_{2,J+1} \frac{A_{J+1}}{A_J} + C_{2,J}) = C_3 C_{2,J+1} + C_1 C_{2,J}$$

Finally with (19)

$$H_{P,J+1,1} = \frac{-C_1 + V_{P,J+1,1}}{C_1}$$

$$H_{P,J+1,1} = \frac{1}{C_{2,J+1}} (-C_1 + (\frac{C_3 C_{2,J+1} + C_1 C_{2,J}}{C_{2,J+1} \frac{A_{J+1}}{A_J} + C_{2,J}}))$$

or

$$H_{P,J+1,1} = \frac{-C_1 (C_{2,J+1} A_{J+1} + C_{2,J} A_J) + (C_3 C_{2,J+1} + C_1 C_{2,J}) A_J}{C_{2,J+1} (C_{2,J+1} A_{J+1} + C_{2,J} A_J)}$$

$$H_{P,J+1,1} = \frac{-C_1 A_{J+1} + C_3 A_J}{C_{2,J+1} A_{J+1} + C_{2,J} A_J}$$

ADDENDUM 3

Derivation of $V_{P,J,NN} = -C_4 + (C_4^2 + C_4 (C_1 + C_3))^{\frac{1}{2}}$

$$\text{Given} \quad \bullet \quad V_{P,J,NN} = \tau V_{oJ} \left(\frac{H_{P,J,NN} - H_{P,J+1,1}}{\Delta H_o} \right)^{\frac{1}{2}} \quad (22)$$

$$\bullet \quad V_{P,J+1,1} = C_1 + C_2 H_{P,J+1,1} \quad (23)$$

$$\bullet \quad V_{P,J,NN} = C_3 - C_2 H_{P,J,NN} \quad (24)$$

$$(22) \quad \rightarrow \quad H_{P,J,NN} = \Delta H_o \left(\frac{V_{P,J,NN}}{\tau V_{oJ}} \right)^2 + H_{P,J+1,1}$$

Substituting into (24) yields

$$V_{P,J,NN} = C_3 - C_2 \left(V_{P,J,NN}^2 \left(\frac{\Delta H_o}{(\tau V_{oJ})^2} \right) + H_{P,J+1,1} \right)$$

$$\text{From (23):} \quad H_{P,J+1,1} = \frac{V_{P,J+1,1} - C_1}{C_2}$$

$$\text{So} \quad V_{P,J,NN} = C_3 - V_{P,J,NN} \frac{C_2 \Delta H_o}{(\tau V_{oJ})^2} - C_2 \left(\frac{V_{P,J+1,1} - C_1}{C_2} \right)$$

Calling $C_4 = \frac{\tau^2 V_{oJ}^2}{\Delta H_o C_2}$ and rearranging yields

$$V_{P,J,NN}^2 + 2 V_{P,J,NN} C_4 - C_4 (C_1 + C_3) = 0$$

This second order equation in $V_{P,J,NN}$ is solved, the positive solution is

$$V_{P,J,NN} = -C_4 + (C_4^2 + (C_1 + C_3) C_4)^{\frac{1}{2}}$$

ADDENDUM 4

Derivation of $V_{P,J,NN} = -\frac{C_4}{2} + \left(\left(\frac{C_4}{2} \right)^2 + C_3 C_4 \right)^{\frac{1}{2}}$

Given • $\frac{V_{P,J,NN}}{V_o} = \tau \left(\frac{H_{P,J,NN}}{H_o} \right)^{\frac{1}{2}}$ (25)

• $V_{P,J,NN} = C_3 - C_2 H_{P,J,NN}$ (26)

From (25) $H_{P,J,NN} = V_{P,J,NN} \frac{H_o}{V_o^2 \tau^2}$

Substituting into (26) yields

$$V_{P,J,NN} = C_3 - \frac{C_2 H_o}{\tau_o^2 V_o^2} V_{P,J,NN}^2$$

or

$$V_{P,J,NN}^2 + V_{P,J,NN} \frac{V_o^2 \tau_o^2}{C_2 H_o} - C_3 \frac{V_o^2 \tau_o^2}{C_2 H_o} = 0$$

Calling $C_4 = \frac{\tau_o^2 V_o^2}{C_2 H_o}$ the above equation becomes

$$V_{P,J,NN}^2 + V_{P,J,NN} C_4 - C_3 C_4 = 0$$

The positive solution is

$$V_{P,J,NN} = -\frac{C_4}{2} + \left(\left(\frac{C_4}{2} \right)^2 + C_3 C_4 \right)^{\frac{1}{2}}$$

ADDENDUM 5

In this section, the general Method of Characteristics is derived. Two kinds of points have been considered:

- interior points
- boundary points

The expression of velocity and pressure head at time $t + \Delta t$ at any point are expressed as functions of known parameters evaluated at time t by previous calculations.

The grid points of the method of characteristics are located by two indices: J designating the pipe (pipe number)

I designating the section of the pipe J (reach number)

With these elements the expressions derived in Appendix A (Method of Characteristics) can be translated directly in computer language as they appear in HYTRAN.

For $I = 1, \dots, N$

$$VR(J,I) = (V(J,I+1) - THETA(J) * A(J) * (V(J,I+1) - (V(J,I)))) / (1 + THETA(J) * (V(J,I+1) - V(J,I)))$$

$$VS(J,I+1) = (V(J,I) - THETA(J) * A(J) * (V(J,I) - V(J,I+1))) / (1 - THETA(J) * (V(J,I) - V(J,I+1)))$$

$$HR(J,I) = H(J,I+1) - THETA(J) * (VR(J,I) + A(J)) * (H(J,I+1) - H(J,I))$$

$$HS(J,I+1) = H(J,I) + THETA(J) * (VS(J,I+1) - A(J)) * (H(J,I) - H(J,I+1))$$

NOTE: For VR and HR the subscript I is the one indicated on the above sketch. However, for VS and HS, I designs point C and I+1 point B (respectively former I+1 and I+2).

For Interior Points

With these known values of velocity and head at points R and S, the velocity and head at point P become for $I = 1, \dots, N-1$.

$$VP(J,I+1) = 0.5 * (VR(J,I) + VS(J,I+2) + C2(J) * (HR(J,I) - HS(J,I+2) - DELT * SIN(ALPHA(J)) * (VR(J,I) - VS(J,I+2)))) - (F(J) * DELT / (2.*D(J))) * (VR(J,I) * ABS(VR(J,I)) + VS(J,I+2) * ABS(VS(J,I+2))))$$

$$HP(J,I+1) = 0.5 * (HR(J,I) + HS(J,I+2) + (A(J)/G) * (VR(J,I) - VS(J,I+2)) - DELT * SIN(ALPHA(J)) * (VR(J,I) + VS(J,I+2) - (A(J)/G) * (F(J) * DELT / (2.*D(J))) * (VR(J,I) * ABS(VR(J,I)) - VS(J,I+2) * ABS(VS(J,I+2)))))$$

NOTE: • The velocity and head are calculated at any interior points, i.e., from section 2 to N.

- The variable $C2(J)$ is defined as $C2(J) = G/A(J)$ (calculated previously in subroutine INIT).

For Boundary Points

The boundary points corresponding to both ends of pipe J are located by subscript 1 (upstream end) and NN (downstream end). $NN = N+1$ where N is the total number of reaches in pipe J.

As stated in Appendix A, the velocity and pressure head are directly related to two parameters introduced for reasons of commodity.

For $I = 1$

$$C1(J) = VS(J, I+1) * (1. + C2(J) * DELT * SIN(ALPHA(J))) - F(J) * DELT * ABS(VS(J, I+1)) / (2. * D(J)) - C2(J) * HS(J, I+1)$$

For $I = N$

$$C3(J) = VR(J, I) * (1. - C2(J) * DELT * SIN(ALPHA(J))) - F(J) * DELT * ABS(VR(J, I)) / (2. * D(J)) + C2(J) * HR(J, I)$$

At each junction (end of pipe) one of these parameters relates the velocity to the pressure head.

$$\text{Upstream end: } VP(J, 1) = C1(J) + C2(J) * HP(J, 1)$$

$$\text{Downstream end: } VP(J, NN) = C3(J) - C2(J) * HP(J, NN)$$

At both ends of pipe J, one extra equation is needed to determine completely VP and HP. This additional equation is furnished by the junction itself (see Appendix A, Boundary Conditions).

APPENDIX B

ORIGINAL HYTRAN VERSION

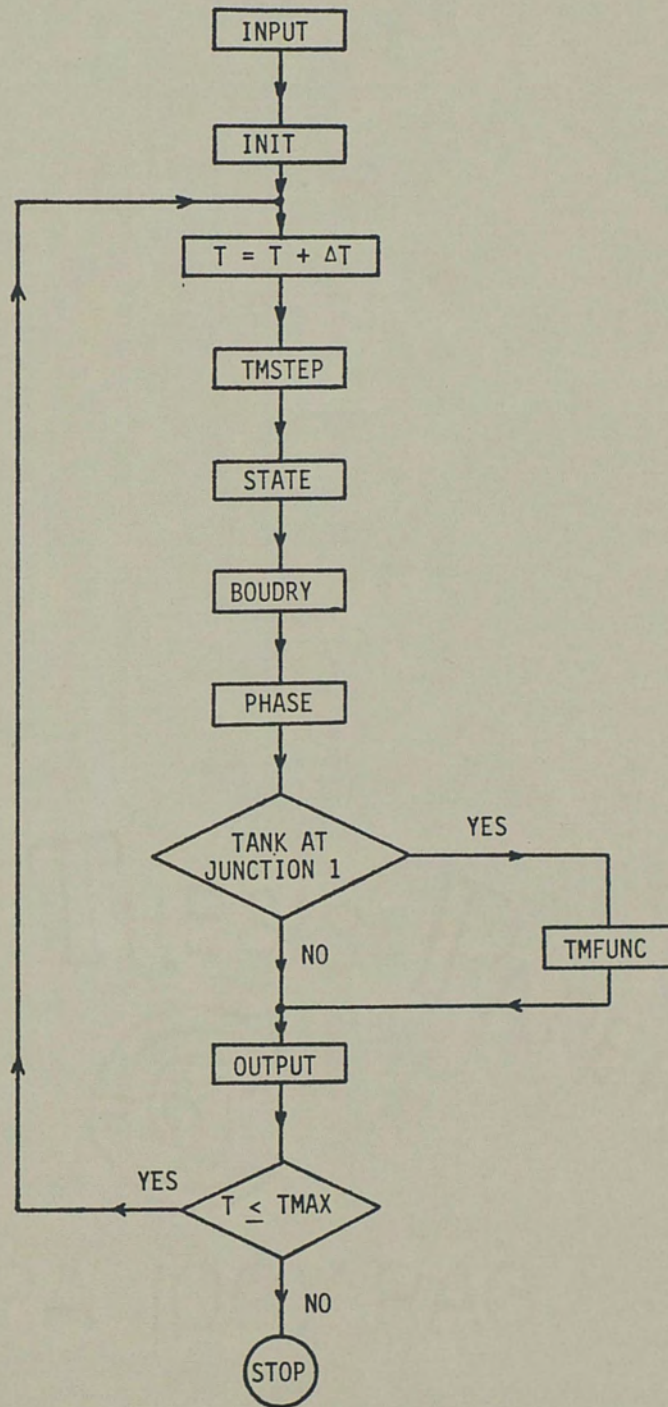


Fig. 15. HYTRAN Flowchart

- INPUT: Reads in the data stored in file: HYTRAN.DAT. (Sample shown in Appendix H.)
- INIT: Calculates the initial (steady state) conditions (head and velocity) at each grid point (reach) of the piping system.
- TMSTEP: Checks the timestep ΔT for stability. If the distance covered by the pressure pulse is larger than any reach length, the former timestep is halved.
- STATE: Determines the head and velocity for transient calculation at interior points of pipes (not at end of pipes) by the method of characteristics.
- BOUDRY: Calculates the head and velocity at junctions (ends) of the pipes in the system using the boundary conditions (tank, valves, orifice, series connection ...)
- PHASE: When vapor formation occurs at a section, the pressure is held at vapor head and cavity is permitted to form.
- TMFUNC: If there is a tank at junction 1 TMFUNC determines the height of liquid in the tank or in the first connected pipe whenever the tank is empty.
- OUTPUT: Writes the results (mainly head and velocity at each pipe junction) in file: HYTRAN.RPT at preselected times. (Sample shown in Appendix H.)

NOTE: The main loop between $T = T + \Delta T$ and $T > TMAX$ holds for transient calculation using the method of characteristics. Head and velocity are calculated at each piping section (reach) at time $T + \Delta T$ using the data obtained previously at time T .

These calculations are done between $T = 0$ and $T = TMAX$ for which the transient is to be analyzed.

Initial Hytran Modifications

The modification made on the former HYTRAN version required some changes in the HYTRAN User's Manual.

The variables:

IVALVE: indicating the type of valve used

TT: indicating the time in seconds after $T = 0$ when the various valves begin their motion

TC: indicating the length of time in seconds required for the valves to open or close

RB: radii of the spheres of the various ball valves

have been eliminated.

On the other hand new variables have been introduced:

NTAU: A one-dimensional array consisting of integer numbers between 1, 10 in ascending numerical order by junction number. Indicates the number of data points used to describe the valve opening fraction TAU as a function of time.

TIME: A two-dimensional array identifying in ascending numerical order by junction number the times at which a TAU value is given. For each junction 10 data need to be entered in ascending numerical order.

TAUV: A two-dimensional array giving the valve opening fractions in ascending numerical order by junction number. (10 values per junction).

A graph for the standard valves is given below

TIME2, ITPR2, TIME3, TIME4, ITPR4: control the output of the printer. As before, ITPRNT defines the intervals at which the output is generated by the printer (i.e., the value of ITPRNT = 5, indicates that every 5th timestep will be printed).

Now for $T > \text{TIME2}$, $\text{ITPRNT} = \text{ITPR2}$
 $T > \text{TIME3}$, $\text{ITPRNT} = \text{ITPR3}$
 $T > \text{TIME4}$, $\text{ITPRNT} = \text{ITPR4}.$

The variable NSINK has been given a new function, as illustrated in Table 3.

TABLE 3
DESCRIPTION OF NSINK VARIABLE

NSINK (L)	Valve Type	Inside of line (Between pipes equal diameter)	End of line (Discharging to atmosphere)	Former IVALVE value
1	Control valve	X		+2, -2, +4, -4, +7, -7, +8, -8,
2	Control valve	X		+1, -1, +3, -3,
3	Orifice		X	-5
4	Orifice	X		+5
5	Check valve		X	+6
6 *	Pressure relief valve		X	-6
7 **	Pressure relief valve	X		≥ 10

* C1P (L) = head for valve to activate (ft)

C2P (L) = head for valve to close completely (ft)

** C1P (L) = closing head (ft)

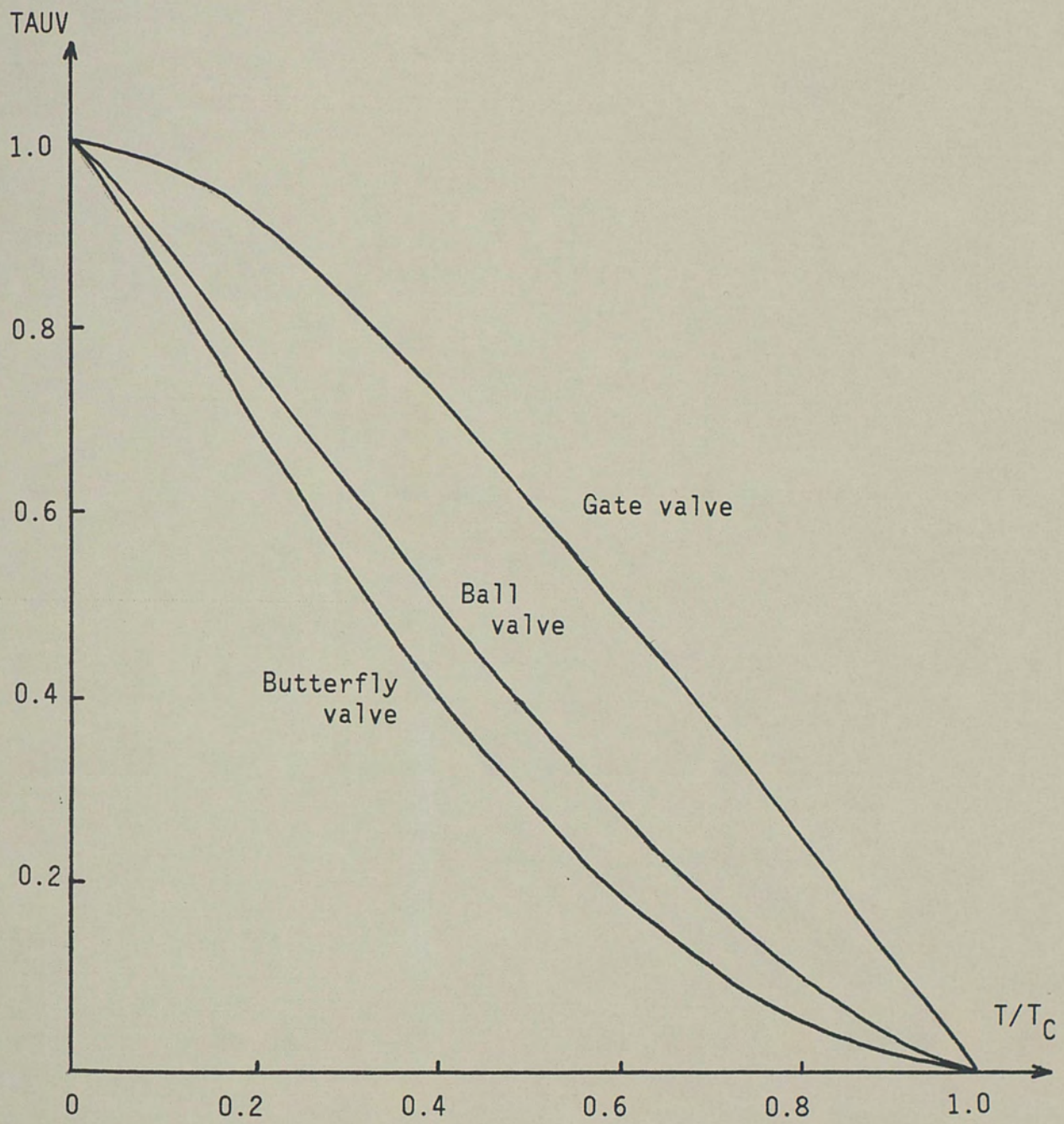


Fig. 16. TAUv values for classical valve types.

Knowing the total closure time TC and the time TT after $T = 0$ when the valves begin their motion, the variable $TIME$ can be calculated as:

$$TIME = TT + \frac{T}{TC}$$

Derivation of the valve constant C_{44}

The valve constant C_{44} used in HYTRAN is related to the head loss through a valve or an orifice. It is defined as:

$$C_{44} = \frac{V_o^2 a}{gH_o} \quad \text{for a valve or an orifice at the end of a pipe}$$

$$\text{and } C_{44} = \frac{V_o^2 a}{g(\Delta H)_o} \quad \text{when inside the piping system.} \quad (27)$$

a : upstream wave speed (ft/sec)

g : gravitational acceleration

V_o, H_o : velocity and head drop for steady-state flow conditions

Two cases are examined:

1. Orifice where the inner diameter is known.
2. Valve, filter, ... where a C_v coefficient is given.

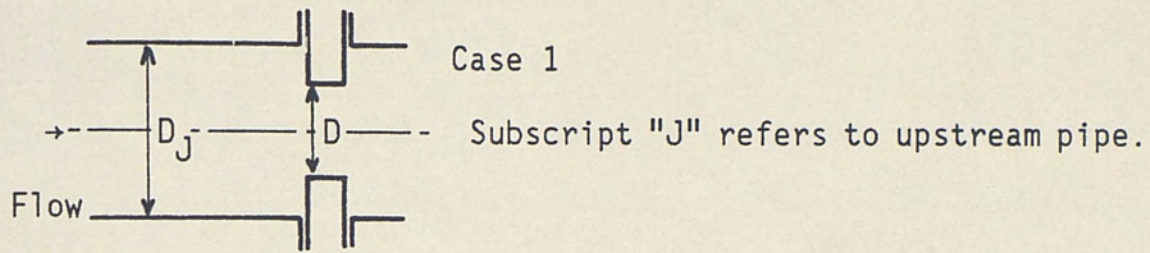


Fig. 17. Valve constant for an orifice.

The rate of flow through the orifice may be expressed by

$$q = \frac{C_d A_G (2g\Delta H_o)^{\frac{1}{2}}}{(1 - (\frac{D}{D_J})^4)^{\frac{1}{2}}} = C A_G (2g\Delta H_o)^{\frac{1}{2}}$$

J

where C is defined as the flow coefficient. Values of C are given in graphs. (Crane, 1965).

Since $q = V_o A_J = \frac{V_o \pi D_J^2}{4}$

$$V_o^2 = \frac{16 q^2}{\pi^2 D_J^4}$$

$$\text{also } (\Delta H)_o = \frac{q^2}{C^2 A_G^2 (2g)} = \frac{q^2 16}{C^2 (\pi^2 D^4) 2g}$$

Combining these equations and substituting into (27) yields

$$C_{44} = \frac{16 q^2}{\pi^2 D_J^4} \frac{a}{g} \frac{C^2 \pi^2 D^4 2g}{q^2 16}$$

or $C_{44} = 2C^2 a \frac{D^4}{D_J^4}$ (28)

Case 2

We assume that a C_v coefficient is given. Per definition the pressure drop for liquids with viscosity similar to water at 60°F is given by

$$\Delta P = \left(\frac{Q}{C_v} \right)^2 \frac{\rho}{62.4}$$

with $(\Delta H)_o = \frac{144 \Delta P}{\rho}$

and $Q = \frac{60}{0.13368} q$

Q: rate of flow in gallons per minute

ρ : weight of density (lb/ft²)

ΔP : pressure drop (lb/ft²)

q: rate of flow (ft /s) ³

$$C_{44} = \frac{16 q^2}{\pi^2 D_J^4} \frac{a}{(32.2) 144 (60q)^2 \rho} \frac{\rho C_v^2 (0.13368) 62.4}{1}$$

$$C_{44} = 1.083 (10)^{-7} \frac{a C_v^2}{D_J^4} \quad (29)$$

D_J : diameter of pipe J (ft)

The expressions (28) and (29) relate C_{44} to known data coming from the system description. HYTRAN code has been modified (see Appendix C) and equation (29) has been incorporated to the program so that the input data, instead of being C_{44} are the directly available C_v valve constants. In the case of an orifice, the combination of (28) and (29) yields the C_v equivalent value corresponding to the orifice of diameter D (ft) and coefficient C

$$C_v = 4297.35 C D^2$$

Determination of the Steady State Condition Parameters

The input data for HYTRAN require steady state velocity and pressure heads. At each junction the head and the fluid velocity have to be calculated by the classical fluid mechanics method (Bernouilli equation).

Two kinds of head losses are considered:

- (a) Due to the friction on the wall of the pipe (for pipe).
- (b) Due to the junction (restrictions).

Other minor losses are neglected.

Bernouilli Theorem

The conservation of the total energy of the fluid can be expressed as (from point 1 to 2)

$$Z_1 + H_1 + \frac{V_1^2}{2g} = Z_2 + H_2 + \frac{V_2^2}{2g} + \Delta H$$

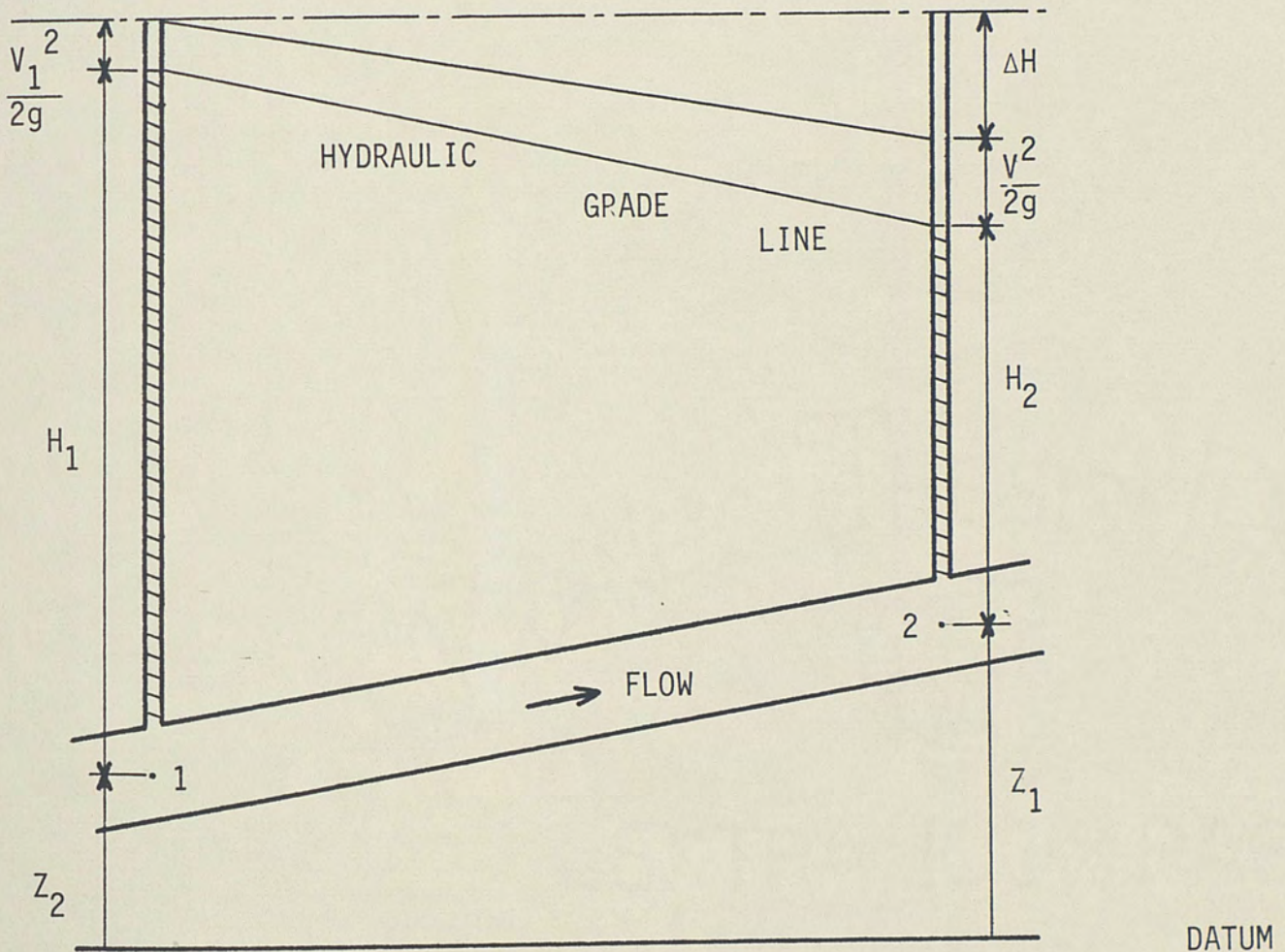


Fig. 18. Energy balance for two points in a fluid.

Case A The head loss ΔH is due to friction. Darcy's formula gives an expression for the head drop in a pipe

$$\Delta H = \frac{fLV^2}{D2g}$$

f: friction factor
L: pipe length (ft)
V: fluid velocity (ft/s)
D: pipe diameter (ft)

or
$$\Delta H = \frac{fL}{D2g} \frac{q^2 16}{\pi^2 D^4}$$
 q: flow rate (ft³/s)

$$\Delta H = 0.02517 \frac{fL}{D^5} q^2$$

Case B Junctions between two pipes, such as a valve, an orifice, or a filter are considered separately. For valves and orifices, a constant C_{44} (see derivation of the valve constant C_{44} , Initial Hytran Modifications) is required and the head drop can be obtained.

From the definition
$$C_{44} = \frac{V_o^2 a}{g (\Delta H)_o}$$

$$(\Delta H)_o = \left(\frac{4q^2}{\pi D_J^2} \right) \frac{a}{32.2 C_{44}}$$
 where "o" refers to steady-state conditions
"J" refers to upstream pipe

or
$$(\Delta H)_o = 464875 \frac{q^2}{C_v^2}$$

Since these are the two head drops taken into account, with these two equations the head H in feet of fluid may be calculated at each junction knowing the liquid level in the tank (i.e., the static head) considered as a source.

From one pipe to the next one in the piping system, going in the direction of the flow, all the losses are added together and subtracted from the static head of the tank (source).

The resultant head at each junction corresponds to the variable "HT" of HYTRAN which is equal to the elevation of the considered junction augmented by the pressure head H .

Hytran Sample Test Case

A copy of a former HYTRAN version was provided with a sample problem solution in HYTRAN User's Manual.

The flow in the considered system was initially at rest and at time $t = 0$ a valve was opened. A second valve was slowly opened at time $t = 2.84$ s and the transient analysis was made for about 10 seconds.

The entire set of data was available from the output copy.

However this original HYTRAN version has been modified in order to get a more versatile program.

The present version differs from the previous one by the way the valve opening coefficient τ is determined as a function of time. The former program calculated $\tau(t)$ using the classical equations for the standard existing valves: ball valve, butterfly valve, globe and gate valve. The present program requires data points for any valve, giving

the opening coefficient τ (calculated previously) as a function of time. For each valve 10 points are required corresponding to a valve of τ ($0 \leq t \leq 1$) at 10 different times. The program then uses an interpolation subroutine to get the value for τ after each timestep of the transient calculation. This version allows the user to take any kind of curve for τ as a function of time and is not limited to the three standard valves.

A minor change has also been made in the output statements, to get more flexible outprints (for example, one only at some given time, and not the whole set of outprints preceding that time).

The first test case done with HYTRAN as an initial check was to model the sample test program and compare the results with the ones of the HYTRAN User's Manual.

Applying the HYTRAN modifications (see Method of Characteristics) to the HYTRAN User's Manual sample problem, the data were changed as the following example shows:

The NSINK valves which conform to the chart take the following values:

NSINK = 0,0,1,0,3,0,4,0,5,3,0,4,0,3,0,4,3,0,4,1,0,3,0,0,4,0,0,0,
3,4,

Since two valves only are opened, namely at junction 3 and 20, only two sets of 10 non-zero values are to be calculated for TIME and TAUV.

The variable TIME is calculated as $TIME = TT + \frac{T}{TC}$

For junction 3 $TT = 0$ $TC = 1.225 \text{ s}$

20 $TT = 2.84 \text{ s}$ $TC = 5.12 \text{ s}$

Choosing 10 regularly spaced points on the graph (ball valve curve for junctions 3, 20) yields the following values:

$NTAU = 2*0, 10, 16*0, 10,$

$TIME = 20*0., 0., 0.1225, 0.245, 0.3675, 0.49, 0.6125, 0.735,$
 $0.8575, 0.98, 1.225, 160*0., 2.84, 2.8912, 2.9424, 2.9936,$
 $3.0448, 3.096, 3.1472, 3.1984, 3.2496, 3.352,$

$TAUV = 20*0., 0., 0.035, 0.105, 0.19, 0.285, 0.395, 0.515, 0.63,$
 $0.76, 1., 160*0., 0., 0.035, 0.105, 0.19, 0.285, 0.395,$
 $0.515, 0.63, 0.76, 1.$

Since output sample prints were for $T = 4.81$, $T = 6.81$, $T = 8.01$ and $T = 8.68 \text{ s}$, the printer control variables are set equal to

$ITPRNT = 4810$ will print, at $T = 4.81 \text{ s}$ since the timestep is

$DELT = 0.001$

$TIME2 = 6.81$	→	$T = 6.81 \text{ s}$
$ITPR2 = 6810$		
$TIME3 = 8.01$	→	$T = 8.01 \text{ s}$
$ITPR3 = 8010$		
$TIME4 = 8.68$	→	$T = 8.68 \text{ s}$
$ITPR4 = 8680$		

NOTE 1: The sample data considered all the orifice τ curves as step functions (sudden opening, $TC = 0.00001$, which is less than one timestep $DELT = 0.001$, at a given time TT .)

But since the fluid was at rest anyway, before the opening it could have been simulated by a simple orifice remaining open at all times. This has been done incidently in the test program leading to the same results as in the sample output.

NOTE 2: The selected outprints compared to the sample output copies permit to conclude for a perfect agreement. (See Table 4.)

TABLE 4
OUTPUT FOR SAMPLE TEST CASE

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HYTRAN INPUT DATA

HYTRAN SAMPLE PROBLEM

```

$DIN
NJCT      =          30,
NPIPE     =          29,
DELT      = 1.0000000E-03,
TMAX      = 8.800000   ,
NP        =          1,          3,          2,          3, 2*2,          1,
          3, 3*2,          1,          3, 2*2,          1, 2*2,          1,
          2,          3, 3*2,          1, 4*2,          1,
NSORCE    =          1, 29*0,
NSINK     = 2*0,          1,          0,          3,          0,          4,
          0,          5,          3,          0,          4,          0,
          3,          0,          4,          3,          0,          4,
          1,          0,          3, 2*0,          4, 3*0,          3,
          4,
NSTANK    = 30*0,
HT        = 2*21.90300   , 6*3.196000   , 4*7.456000   , 7*3.196000   ,
11*9.586000   ,
C1P       = 30*0.0000000E+00,
C2P       = 30*0.0000000E+00,
C3P       = 21.90300    , 29*0.0000000E+00,
C4P       = 30*0.0000000E+00,
VDLO      = 30*0.0000000E+00,
HO        = 30*0.0000000E+00,
GAMMA     = 30*0.0000000E+00,
RPC        = 30*0.0000000E+00,
RPD        = 30*0.0000000E+00,
VC         = 30*0.0000000E+00,
H2MIN     = 30*0.0000000E+00,
VOMAX     = 30*0.0000000E+00,
D         = 0.8350000   , 2*0.6650000   , 3*0.2710000   , 0.5420000   ,
4*0.2710000   , 0.5100000   , 3*0.4270000   , 3*0.2710000   ,
2*0.6650000   , 2*0.4060000   , 2*0.4270000   , 3*0.4060000   ,
2*0.4270000   , 11*0.0000000E+00,
XL        = 20.23600   , 5.326000   , 37.27600   , 2*1.066000   ,
3.196000   , 7.456000   , 2.131000   , 4.261000   , 1.066000   ,
7.456000   , 6.391000   , 2*2.131000   , 2*3.196000   , 7.456000   ,
3.196000   , 5.326000   , 35.14600   , 1.066000   , 5.326000   ,
2*3.196000   , 14.91100   , 6.391000   , 3.196000   , 1.066000   ,
2.131000   , 11*0.0000000E+00,
VO        = 40*0.0000000E+00,
A         = 29*1065.000   , 11*0.0000000E+00,
ALPHA     = -90.00000   , 4*0.0000000E+00, 90.00000   , 4*0.0000000E+00,
90.00000   , 3*0.0000000E+00, 90.00000   , 2*0.0000000E+00, 90.00000   ,
2*0.0000000E+00, 2*90.00000   , 0.0000000E+00, 90.00000   ,
0.0000000E+00, 90.00000   , 0.0000000E+00, 2*90.00000   ,
11*0.0000000E+00,
JJ        = 2*1,          2,          3,          4,          5,          6,
          7,          8,          9,          10,          11,          12,
          13,          14,          15,          16,          17,          18,
          19,          20,          21,          22,          23,          24,
          25,          26,          27,          28,          29,          0,
          2,          3,          4,          5,          6,          0,
          8,          9,          10,          11,          0,          13,
          14,          15,          0,          17,          18,          0,

```


TABLE 4 (CONTINUED)

HYTRAN. RPT: 56

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Page 2

```

      20,      25,      22,      23,      24,      0,
      26,      27,      28,      29, 2*0,      19,
      0,      7, 3*0,      12, 4*0,      16, 7*0,      21,
69*0,
IC      =      -1, 29*1,      0, 5*-1,      0, 4*-1,      0,
3*-1,      0, 2*-1,      0, 5*-1,      0, 4*-1, 2*0,      -1,
      0,      -1, 3*0,      -1, 4*0,      -1, 7*0,      -1,
69*0,
C44      = 2*0.0000000E+00, 269.0000 , 0.0000000E+00, 219.0000 ,
0.0000000E+00, 231.0000 , 0.0000000E+00, 1791.000 , 1186.000 ,
0.0000000E+00, 118.4000 , 0.0000000E+00, 348.0000 , 0.0000000E+00,
610.0000 , 227.0000 , 0.0000000E+00, 239.0000 , 178.6000 ,
0.0000000E+00, 941.0000 , 2*0.0000000E+00, 124.5000 ,
3*0.0000000E+00, 892.0000 , 124.5000 ,
ELEV      = 20.23600 , 5*0.0000000E+00, 3.196000 , 4*0.0000000E+00,
7.456000 , 3*0.0000000E+00, 3.196000 , 2*0.0000000E+00, 3.196000
, 2*0.0000000E+00, 1.066000 , 2*6.391000 , 9.586000 ,
0.0000000E+00, 2*6.391000 , 7.456000 , 9.586000 ,
N      =      19,      5,      35, 2*1,      3,      7,
      2,      4,      1,      7,      6, 2*2,
2*3,      7,      3,      5,      33,      1,
      5, 2*3,      14,      6,      3,      1,
      2, 11*0,
F      = 3*8.0000004E-03, 3*8.9999996E-03, 8.0000004E-03, 4*8.9999996E-03,
4*8.0000004E-03, 3*8.9999996E-03, 11*8.0000004E-03, 11*0.0000000E+00,
NTAU      = 2*0,      10, 16*0,      10, 10*0,
TIME      = 21*0.0000000E+00, 0.1225000 , 0.2450000 , 0.3675000 ,
0.4900000 , 0.6125000 , 0.7350000 , 0.8575000 , 0.9800000 ,
1.225000 , 160*0.0000000E+00, 2.840000 , 2.891200 ,
2.942400 , 2.993600 , 3.044800 , 3.096000 , 3.147200 ,
3.198400 , 3.249600 , 3.352000 , 100*0.0000000E+00,
TAUV      = 21*0.0000000E+00, 3.5000000E-02, 0.1050000 , 0.1900000 ,
0.2850000 , 0.3950000 , 0.5150000 , 0.6300000 , 0.7600000 ,
1.000000 , 161*0.0000000E+00, 3.5000000E-02, 0.1050000 ,
0.1900000 , 0.2850000 , 0.3950000 , 0.5150000 , 0.6300000 ,
0.7600000 , 1.000000 , 100*0.0000000E+00
$END

```

```

ISTOP      RHD, LB/FT**3      VARPR, FT      IRUN      ISTART      IDATPE      ITANK1
1          0.62400E+02      -0.32000E+02      1          0          0          2

RADTK1, FT      XHIGH1, FT      XHIGH2, FT      TKLENG, FT      VFLOIN, FT**3/S
0.20000E+01      0.00000E+00      0.16670E+01      0.00000E+00      0.00000E+00

OUTPUT PARAMETERS--LPRT, ITPRNT, LPLT, ITPLT, LTAPE, ITTPE , TIME2, ITPR2, TIME3, ITPR3
1 4810      0      0      0      0      6.81 6810      8.01 8010

```


TABLE 4 (CONTINUED)

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SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.00000E+00 SEC

PIPE NO.	PRESSURE HEAD UP FT.	PRESSURE HEAD DN PSI	PRESSURE HEAD DN FT.	PRESSURE HEAD DN PSI	VEL. UP STREAM FT/SEC	VEL. DN STREAM FT/SEC
1	0.16670E+01	0.72237E+00	0.21903E+02	0.94913E+01	0.00000E+00	0.00000E+00
2	0.21903E+02	0.94913E+01	0.21903E+02	0.94913E+01	0.00000E+00	0.00000E+00
3	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
4	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
5	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
6	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
7	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
8	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
9	0.74560E+01	0.32309E+01	0.74560E+01	0.32309E+01	0.00000E+00	0.00000E+00
10	0.74560E+01	0.32309E+01	0.74560E+01	0.32309E+01	0.00000E+00	0.00000E+00
11	0.74560E+01	0.32309E+01	-0.47684E-06	-0.20663E-06	0.00000E+00	0.00000E+00
12	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
13	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
14	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
15	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
16	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
17	0.31960E+01	0.13849E+01	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00
18	0.31960E+01	0.13849E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
19	0.21903E+02	0.94913E+01	0.21903E+02	0.94913E+01	0.00000E+00	0.00000E+00
20	0.95860E+01	0.41539E+01	0.95860E+01	0.41539E+01	0.00000E+00	0.00000E+00
21	0.95860E+01	0.41539E+01	0.85200E+01	0.36920E+01	0.00000E+00	0.00000E+00
22	0.85200E+01	0.36920E+01	0.31940E+01	0.13841E+01	0.00000E+00	0.00000E+00
23	0.31950E+01	0.13845E+01	0.31950E+01	0.13845E+01	0.00000E+00	0.00000E+00
24	0.31950E+01	0.13845E+01	-0.99945E-03	-0.43310E-03	0.00000E+00	0.00000E+00
25	0.95860E+01	0.41539E+01	0.95860E+01	0.41539E+01	0.00000E+00	0.00000E+00
26	0.95860E+01	0.41539E+01	0.31950E+01	0.13845E+01	0.00000E+00	0.00000E+00
27	0.31950E+01	0.13845E+01	0.31950E+01	0.13845E+01	0.00000E+00	0.00000E+00
28	0.31950E+01	0.13845E+01	0.21290E+01	0.92257E+00	0.00000E+00	0.00000E+00
29	0.21300E+01	0.92300E+00	-0.99945E-03	-0.43310E-03	0.00000E+00	0.00000E+00

VOL.TKT, VOL.TKO, VOL.TKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY

0.20948E+02 0.00000E+00 0.20948E+02 0.21903E+02 0.20236E+02 0.20236E+02 0.10651E+01

TIME STEP HAS BEEN HALVED, DELT= 0.50000E-03

TABLE 4 (CONTINUED)

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Page 4

SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.48146E+01 SEC

PIPE NO.	PRESSURE HEAD UP FT.	PRESSURE HEAD DN PSI	PRESSURE HEAD FT.	PRESSURE HEAD DN PSI	VEL. UP STREAM FT/SEC	VEL. DN STREAM FT/SEC
1	0.70297E+00	0.30462E+00	0.20470E+02	0.88704E+01	0.79794E+01	0.79748E+01
2	0.20470E+02	0.88704E+01	0.20408E+02	0.88435E+01	0.71759E+01	0.71757E+01
3	0.14077E+02	0.60999E+01	0.13646E+02	0.59132E+01	0.71757E+01	0.71745E+01
4	0.13646E+02	0.59132E+01	0.13619E+02	0.59014E+01	0.67757E+01	0.67757E+01
5	0.66843E+01	0.28965E+01	0.66570E+01	0.28847E+01	0.67757E+01	0.67757E+01
6	0.66570E+01	0.28847E+01	0.33784E+01	0.14640E+01	0.67757E+01	0.67763E+01
7	0.13646E+02	0.59132E+01	0.13441E+02	0.58439E+01	0.91063E+01	0.91063E+01
8	0.13486E+02	0.58439E+01	0.12596E+02	0.58244E+01	0.63537E+01	0.63536E+01
9	0.12690E+02	0.54992E+01	0.11448E+02	0.54581E+01	0.63538E+01	0.63538E+01
10	0.11472E+02	0.49711E+01	0.38260E+01	0.49606E+01	0.63538E+01	0.63538E+01
11	0.11448E+02	0.49606E+01	0.13360E+02	0.57894E+01	0.63538E+01	0.63551E+01
12	0.13486E+02	0.58439E+01	0.13360E+02	0.57894E+01	0.84909E+01	0.84909E+01
13	0.13360E+02	0.57894E+01	0.13301E+02	0.57638E+01	0.93869E+01	0.93869E+01
14	0.49268E+01	0.21350E+01	0.48676E+01	0.21093E+01	0.93870E+01	0.93870E+01
15	0.48676E+01	0.21093E+01	0.15829E+01	0.68590E+00	0.93878E+01	0.93878E+01
16	0.13360E+02	0.57894E+01	0.13279E+02	0.57543E+01	0.67672E+01	0.67672E+01
17	0.66067E+01	0.28629E+01	0.64189E+01	0.27815E+01	0.67672E+01	0.67672E+01
18	0.64189E+01	0.27815E+01	0.31426E+01	0.13618E+01	0.67672E+01	0.67678E+01
19	0.20470E+02	0.88704E+01	0.20339E+02	0.88135E+01	0.53974E+01	0.53973E+01
20	0.14944E+02	0.64758E+01	0.14074E+02	0.60987E+01	0.53973E+01	0.53965E+01
21	0.14074E+02	0.60987E+01	0.12981E+02	0.56249E+01	0.73890E+01	0.73892E+01
22	0.11062E+02	0.47936E+01	0.56005E+01	0.24269E+01	0.73890E+01	0.73890E+01
23	0.55354E+01	0.24273E+01	0.55354E+01	0.23987E+01	0.66811E+01	0.66810E+01
24	0.55354E+01	0.23987E+01	0.22727E+01	0.98484E+00	0.66810E+01	0.66815E+01
25	0.14074E+02	0.60987E+01	0.13185E+02	0.57133E+01	0.70888E+01	0.70879E+01
26	0.13185E+02	0.57133E+01	0.64063E+01	0.27761E+01	0.70879E+01	0.70886E+01
27	0.64063E+01	0.27761E+01	0.62121E+01	0.26919E+01	0.70886E+01	0.70882E+01
28	0.62121E+01	0.26919E+01	0.50893E+01	0.22054E+01	0.64081E+01	0.64082E+01
29	0.35670E+01	0.15457E+01	0.13228E+01	0.57323E+00	0.64082E+01	0.64083E+01

DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED

VOL.TKT. VOL.TKG. VOL.TKL. C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY

0.20948E+02 0.12119E+02 0.88335E+01 0.20939E+02 0.20236E+02 0.20236E+02 0.10651E+01

TABLE 4 (CONTINUED)

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SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.68154E+01 SEC

PIPE NO.	PRESSURE HEAD UP FT.	PRESSURE HEAD DN PSI	PRESSURE HEAD DN STREAM END PSI	VEL. UP STREAM FT/SEC	VEL. DN STREAM END FT/SEC
1	-0.47684E-03	-0.20663E-03	0.20080E+02	0.80618E+01	0.80584E+01
2	0.20080E+02	0.87012E+01	0.20039E+02	0.71481E+01	0.71482E+01
3	0.13756E+02	0.59608E+01	0.13466E+02	0.71482E+01	0.71485E+01
4	0.13466E+02	0.58351E+01	0.13442E+02	0.67359E+01	0.67359E+01
5	0.65902E+01	0.28558E+01	0.65670E+01	0.67359E+01	0.67359E+01
6	0.65670E+01	0.28457E+01	0.33016E+01	0.67359E+01	0.67359E+01
7	0.13466E+02	0.58351E+01	0.13341E+02	0.90772E+01	0.90773E+01
8	0.13341E+02	0.57813E+01	0.13299E+02	0.63301E+01	0.63301E+01
9	0.12560E+02	0.54426E+01	0.12479E+02	0.63301E+01	0.63301E+01
10	0.11360E+02	0.49227E+01	0.11340E+02	0.63301E+01	0.63301E+01
11	0.11340E+02	0.49141E+01	0.37424E+01	0.63301E+01	0.63301E+01
12	0.13341E+02	0.57813E+01	0.13243E+02	0.63301E+01	0.63315E+01
13	0.13243E+02	0.57386E+01	0.13194E+02	0.84648E+01	0.84648E+01
14	0.48715E+01	0.21110E+01	0.48224E+01	0.93571E+01	0.93571E+01
15	0.48224E+01	0.20897E+01	0.15520E+01	0.93571E+01	0.93571E+01
16	0.13243E+02	0.57386E+01	0.13174E+02	0.93572E+01	0.93581E+01
17	0.65372E+01	0.28328E+01	0.63743E+01	0.67487E+01	0.67487E+01
18	0.63743E+01	0.27622E+01	0.31082E+01	0.67487E+01	0.67494E+01
19	0.20080E+02	0.87012E+01	0.20056E+02	0.55571E+01	0.55571E+01
20	0.14338E+02	0.62130E+01	0.14183E+02	0.55571E+01	0.55574E+01
21	0.14183E+02	0.61460E+01	0.13101E+02	0.74510E+01	0.74512E+01
22	0.11150E+02	0.48316E+01	0.57429E+01	0.74512E+01	0.74524E+01
23	0.57439E+01	0.24890E+01	0.57073E+01	0.67374E+01	0.67374E+01
24	0.57073E+01	0.24732E+01	0.24744E+01	0.67374E+01	0.67381E+01
25	0.14183E+02	0.61460E+01	0.13956E+02	0.74587E+01	0.74587E+01
26	0.13956E+02	0.60476E+01	0.74680E+01	0.74587E+01	0.74601E+01
27	0.74680E+01	0.32361E+01	0.74196E+01	0.74601E+01	0.74601E+01
28	0.74196E+01	0.32151E+01	0.63400E+01	0.67446E+01	0.67446E+01
29	0.46561E+01	0.20177E+01	0.24992E+01	0.67446E+01	0.67450E+01

DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED

VOLTWT, VOLTWG, VOLTWL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY
 0.20948E+02 0.20948E+02 0.12398E-03 0.20195E+02 0.20196E+02 0.10629E+01

TABLE 4 (CONTINUED)

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SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.80159E+01 SEC

PIPE NO.	PRESSURE HEAD UP FT.	PRESSURE HEAD DN PSI	PRESSURE HEAD FT.	DN STREAM END PSI	UP STREAM END FT/SEC	DN STREAM END VEL. FT/SEC
1	-0.47684E-03	-0.20663E-03	0.11746E+02	0.50897E+01	0.66827E+01	0.66826E+01
2	0.11746E+02	0.50897E+01	0.11928E+02	0.51689E+01	0.60294E+01	0.60294E+01
3	0.74573E+01	0.32315E+01	0.87130E+01	0.37757E+01	0.60294E+01	0.60338E+01
4	0.87130E+01	0.37757E+01	0.87371E+01	0.37861E+01	0.54788E+01	0.54789E+01
5	0.42034E+01	0.18215E+01	0.42275E+01	0.18319E+01	0.54789E+01	0.54789E+01
6	0.42275E+01	0.18319E+01	0.11030E+01	0.47796E+00	0.54789E+01	0.54796E+01
7	0.87130E+01	0.37757E+01	0.89854E+01	0.38937E+01	0.77142E+01	0.77142E+01
8	0.89854E+01	0.38937E+01	0.90292E+01	0.39127E+01	0.53382E+01	0.53384E+01
9	0.85014E+01	0.36840E+01	0.85900E+01	0.37224E+01	0.53389E+01	0.53389E+01
10	0.77944E+01	0.33776E+01	0.78169E+01	0.33873E+01	0.53389E+01	0.53390E+01
11	0.78169E+01	0.33873E+01	0.51222E+00	0.22196E+00	0.53390E+01	0.53408E+01
12	0.89854E+01	0.38937E+01	0.92007E+01	0.39870E+01	0.72053E+01	0.72060E+01
13	0.92007E+01	0.39870E+01	0.92706E+01	0.40172E+01	0.79544E+01	0.79546E+01
14	0.32571E+01	0.14114E+01	0.33271E+01	0.14417E+01	0.79546E+01	0.79547E+01
15	0.33271E+01	0.14417E+01	0.23568E+00	0.10213E+00	0.79547E+01	0.79555E+01
16	0.92007E+01	0.39870E+01	0.92629E+01	0.40139E+01	0.57728E+01	0.57731E+01
17	0.44070E+01	0.19097E+01	0.45520E+01	0.19725E+01	0.57731E+01	0.57735E+01
18	0.45520E+01	0.19725E+01	0.14181E+01	0.61450E+00	0.57735E+01	0.57742E+01
19	0.11746E+02	0.50897E+01	0.11928E+02	0.51966E+01	0.45075E+01	0.45085E+01
20	0.82279E+01	0.35654E+01	0.98424E+01	0.42650E+01	0.45085E+01	0.45110E+01
21	0.98424E+01	0.42650E+01	0.88559E+01	0.38375E+01	0.57863E+01	0.57865E+01
22	0.76794E+01	0.33277E+01	0.27525E+01	0.11928E+01	0.57863E+01	0.57874E+01
23	0.27535E+01	0.11932E+01	0.29743E+01	0.12889E+01	0.52321E+01	0.52321E+01
24	0.29743E+01	0.12889E+01	-0.99945E-03	-0.43310E-03	0.52321E+01	0.52326E+01
25	0.98424E+01	0.42650E+01	0.10360E+02	0.44892E+01	0.63159E+01	0.63165E+01
26	0.10360E+02	0.44892E+01	0.41898E+01	0.18156E+01	0.63159E+01	0.63178E+01
27	0.41898E+01	0.18156E+01	0.43002E+01	0.18634E+01	0.63178E+01	0.63178E+01
28	0.43002E+01	0.18634E+01	0.32695E+01	0.14168E+01	0.57117E+01	0.57119E+01
29	0.20599E+01	0.89264E+00	-0.99945E-03	-0.43310E-03	0.57119E+01	0.57122E+01

DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED

VOLTKT, VOLTKG, VOLTKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY

0.20948E+02 0.20948E+02 0.12398E-03 0.11170E+02

0.11171E+02 0.11171E+02 0.58793E+00

TIME STEP HAS BEEN HALVED, DELT= 0.250000E-03

APPENDIX C

ADDITIONAL HYTRAN MODIFICATIONS

Four major changes were made to HYTRAN in order to simplify input data and allow the code to handle a larger variety of cases.

1. Instead of calculating by hand the C_{44} variables, a new section has been added so that the input variables are the C_v valve constants.
2. The surge tank section has been substituted by three new devices (including a surge tank) adapted from Wylie and Streeter (1978). This has been done since problems with input data came up in the initial version (RPC defined in HYTRAN User's Manual has different units than in the program itself).
3. The subroutine PHASE was rewritten in order to model a flow with cavities at specific locations.
4. The subroutine OUTPUT has been changed namely in the presentation and content of the outprint.

Valve Constants

In Appendix B, a relationship between C_{44} and C_v has been derived. It is used in subroutine INIT to initialize the C_{44} variables with the

following additional conditions. When a valve is located inside the line it has to be connected to two pipes only (up and downstream of the valve) and the characteristics of the two pipes must be the same (inside diameter and sonic velocity in the pipes). Control tests have been inserted to stop the execution of the program, after having printed that the data at the specific valve were bad, in the case when one of the above requirements were not fulfilled.

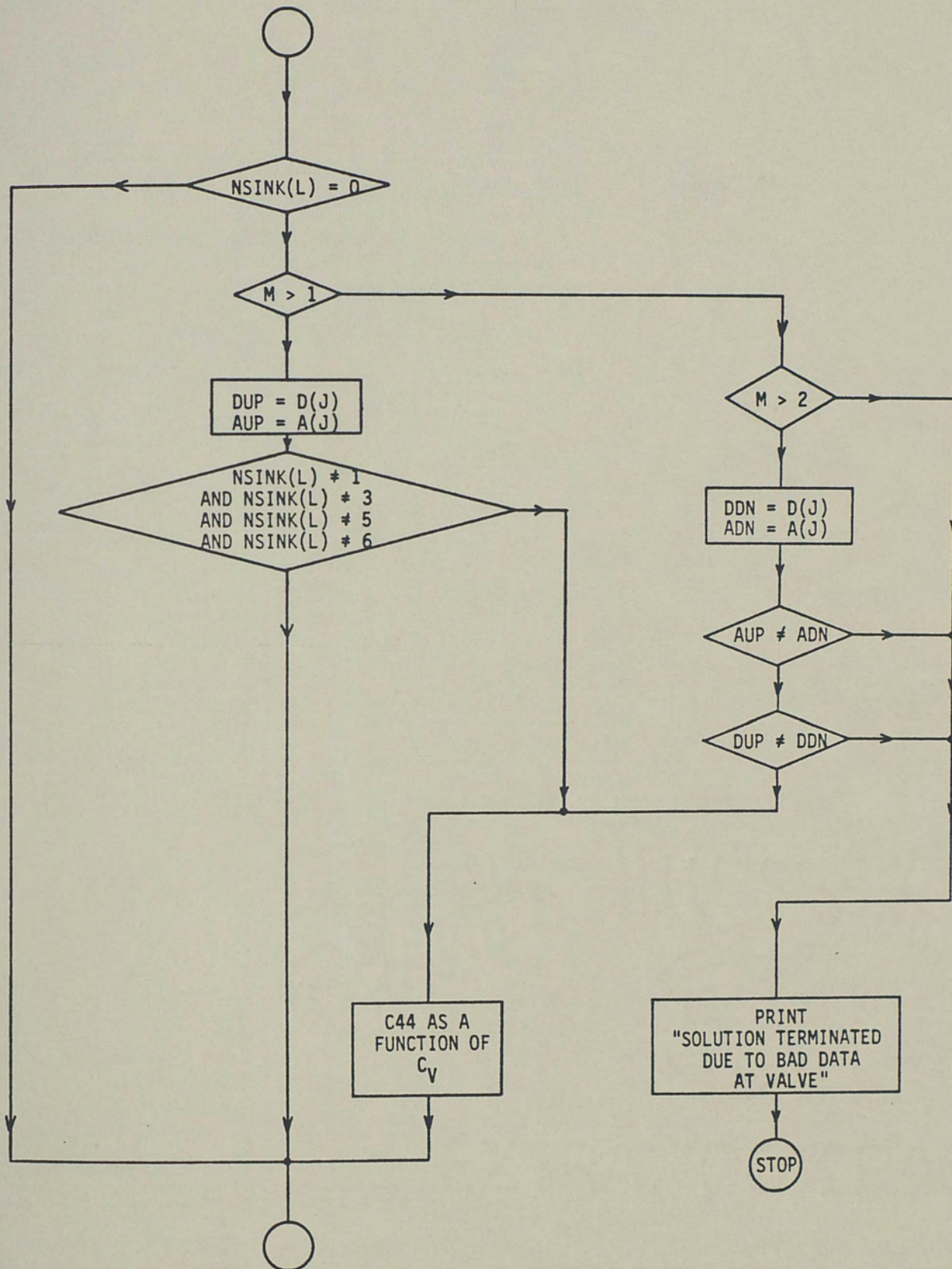


Fig. 19. Flowchart for C_v modification

$$C_{11} = H_{ST} - H + \frac{F_{LI} X_{LI}}{g D_{LI} A_{12}^2} Q_P Q - C_{22} Q \quad (32)$$

Q_P and Q are the flow rates of fluid entering the surge tank at time $t + \Delta t$ and t respectively.

In the accumulator the gas follows the reversible polytropic relation:

$$(H_{ST} + H_B - Z) \left(V - \frac{Q_P + Q}{2} \Delta t \right)^\gamma = C_0 \quad (33)$$

in which H_B is the barometric pressure head

V is the gas volume

γ is the polytropic exponent

Since the device is located at the junction of two pipes J and $J+1$, the velocities of the fluid in the last section of pipe J and the first section of pipe $J+1$ satisfy following equations:

$$V_{P,J,NN} = C_{3,J} - C_{2,J} H_p \quad (34)$$

$$V_{P,J+1,1} = C_{1,J+1} + C_{2,J+1} H_p \quad (35)$$

Defining A_1 and A_2 as

$$A_1 = \frac{\pi}{4} D_J^2$$

$$A_2 = \frac{\pi}{4} D_{J+1}^2$$

The continuity equation requires that

$$V_{P,J,NN} A_1 = V_{P,J+1,1} A_2 + Q_P \quad (36)$$

Substituting (34) and (35) into (36) yields

$$Q_p = -D_1 H_p + B_1 \quad (37)$$

in which

$$B_1 = A_1 C_{3,J} - A_2 C_{1,J+1}$$

$$\text{and } D_1 = A_1 C_{2,J} + A_2 C_{2,J+1}$$

Substituting (37) into (30) yields

$$H_p - H_{ST} = C_{11} + C_{22} (-D_1 H_p + B_1)$$

$$\text{or } H_{ST} = (E_1 + 1) H_p + E_2 \quad (38)$$

$$\text{in which } E_1 = C_{22} D_1$$

$$E_2 = -C_{11} - C_{22} B_1$$

Also holds from (37) $H_p = \frac{B_1 - Q_p}{D_1}$ which with (38) yields

$$H_{ST} = \left(\frac{E_1 + 1}{D_1} \right) (B_1 - Q_p) + E_2 \quad (39)$$

Substituting (39) into (33) yields an implicit relation in Q_p

$$\left(\left(\frac{E_1 + 1}{D_1} \right) (B_1 - Q_p) + E_2 + H_B - Z \right) \left(V - \left(\frac{Q_p + Q}{2} \right) \Delta t \right)^x = CO \quad (40)$$

Is is solved (Newton's method) as follows:

$$F_1 = \left(\frac{E_1 + 1}{D_1} \right) (B_1 - Q_p) + E_2 + H_B - Z \left(V - \left(\frac{Q_p + Q}{2} \right) \Delta t \right)^x - CO = 0$$

A correction to an estimated value of Q_p is obtained noticing that

$$F_1 + \frac{dF_1}{dQ_p} \Delta Q = 0$$

$$\text{or } \Delta Q = \frac{-F_1}{\frac{dF_1}{dQ_p}}$$

$$\frac{dF_1}{dQ_p} = - \frac{\gamma \Delta t}{2} \frac{CO}{(V - \frac{Q_p + Q}{2}) \Delta t)} - \left(\frac{E_1 + 1}{D_1} \right) \left(V - \left(\frac{Q_p + Q}{2} \right) \Delta t \right)^\gamma$$

ΔQ is added to the original value of Q_p and a new iteration is carried out with the new Q_p .

After a given number of iterations, Q_p tends to a limit which is the actual value satisfying (40) and H_p , $V_{p,J,NN}$ and $V_{p,J+1,1}$ are calculated.

A conditional test gives E_1 and E_2 the value 0 if $X_{LI} = 0$ (pipe riser length equal to 0). In that case the surge tank reduces to a simple air chamber located directly at the junction.

Another test checks the gas volume and keeps it between two extreme values VOLMIN and VOLMAX.

Lumped Inertia

When short pipelines may be considered to be inelastic and to contain an incompressible fluid, the liquid mass is considered as a solid with inertia.

$$\text{Equation (30) becomes } H_{p,J,NN} - H_{p,J+1,1} = C_{11} + C_{22} Q_p \quad (41)$$

$$\text{And continuity equation requires } A_1 V_{p,J,NN} = A_2 V_{p,J+1,1} = Q_p \quad (42)$$

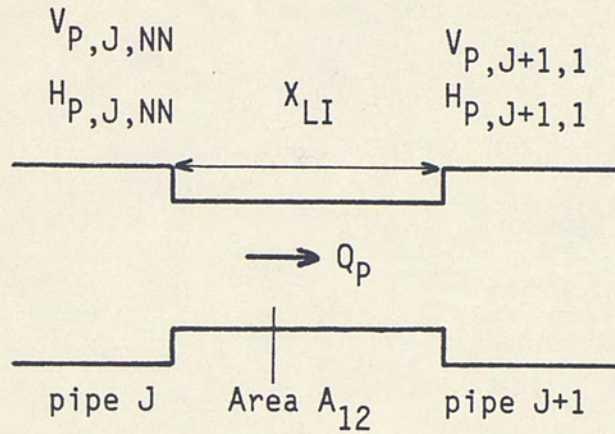


Fig. 21. Schematic representation of a lumped inertia.

Combining (42) with (34) and (35) yields

$$H_{P,J,NN} = \frac{C_{3,J} - \frac{Q_p}{A_1}}{C_{2,J}} \quad (43)$$

$$H_{P,J+1,1} = \frac{\frac{Q_p}{A_2} - C_{1,J+1}}{C_{2,J+1}} \quad (44)$$

Substituting (43) and (44) back into (41) and solving for Q_p yields

$$Q = \frac{\frac{C_{3,J}}{C_{2,J}} + \frac{C_{1,J+1}}{C_{2,J+1}} - C_{11}}{\frac{1}{A_1 C_{2,J}} + \frac{1}{A_2 C_{2,J+1}} + C_{22}} \quad (45)$$

Once Q_p is determined, $V_{P,J,NN}$, $V_{P,J+1,1}$, $H_{P,J,NN}$, and $H_{P,J+1,1}$ are immediately calculated using (42), (43), and (44).

Lumped Capacitance

When elastic effects are much more important than inertial effects, the behavior of a small volume can be lumped.

$$K^1 = \frac{\Delta p}{\Delta V/V}$$

K^1 : bulk modulus of elasticity of the container
and the fluid
 V : container volume

where $\Delta V = \left(\frac{Q_p + Q}{2} \right) \Delta t$

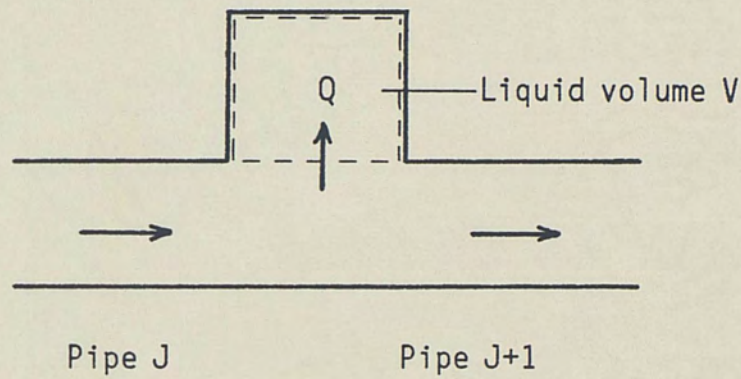


Fig. 22. Schematic representation of a lumped capacitance.

$$H_p = H + \frac{K^1 \Delta t}{V_p} \left(\frac{Q + Q_p}{2} \right) \quad (46)$$

Substituting (46) into (34) and (35), then using (36) yields

$$Q_p = \frac{(H + K_A Q) (-D_1) + B_1}{1 + K_A D_1}$$

in which $K_A = \frac{K^1 \Delta t}{2V_p}$

Again $V_{p,J,NN}$, $V_{p,J+1,1}$, and H_p are then directly calculated.

New Variables

The variables VOLO, HO, RPC, RPD, VC, H2MIN, and VOMAX have been replaced by following one-dimensional arrays:

- If NSTANK = 1 (surge tank or air chamber)
 - VOL: initial volume of gas in cubic feet of the air chamber in the system in ascending numerical order by junction number
 - VOLMIN: minimum volume of gas in cubic feet of the gas accumulator
 - VOLMAX: maximum volume of gas in cubic feet of the gas accumulator
 - CO: defined by equation (33) using initial static volume and pressure head
 - XLI: length of the surge tank pipe riser
 - DLI: inside diameter of the surge tank pipe riser
 - FLI: Friction coefficient in the surge tank pipe riser
- If NSTANK = 2 (lumped inertia)
 - XLI: length of the lumped inertia element
 - DLI: inside diameter of the element
 - FLI: friction coefficient in the element
- If NSTANK = 3 (lumped capacitance)

VOL: initial volume of liquid in cubic feet of the containers in the system in ascending numerical order by junction number

KK: effective bulk modulus of elasticity of the fluid and container (lb/ft^2) in ascending numerical order by junction number

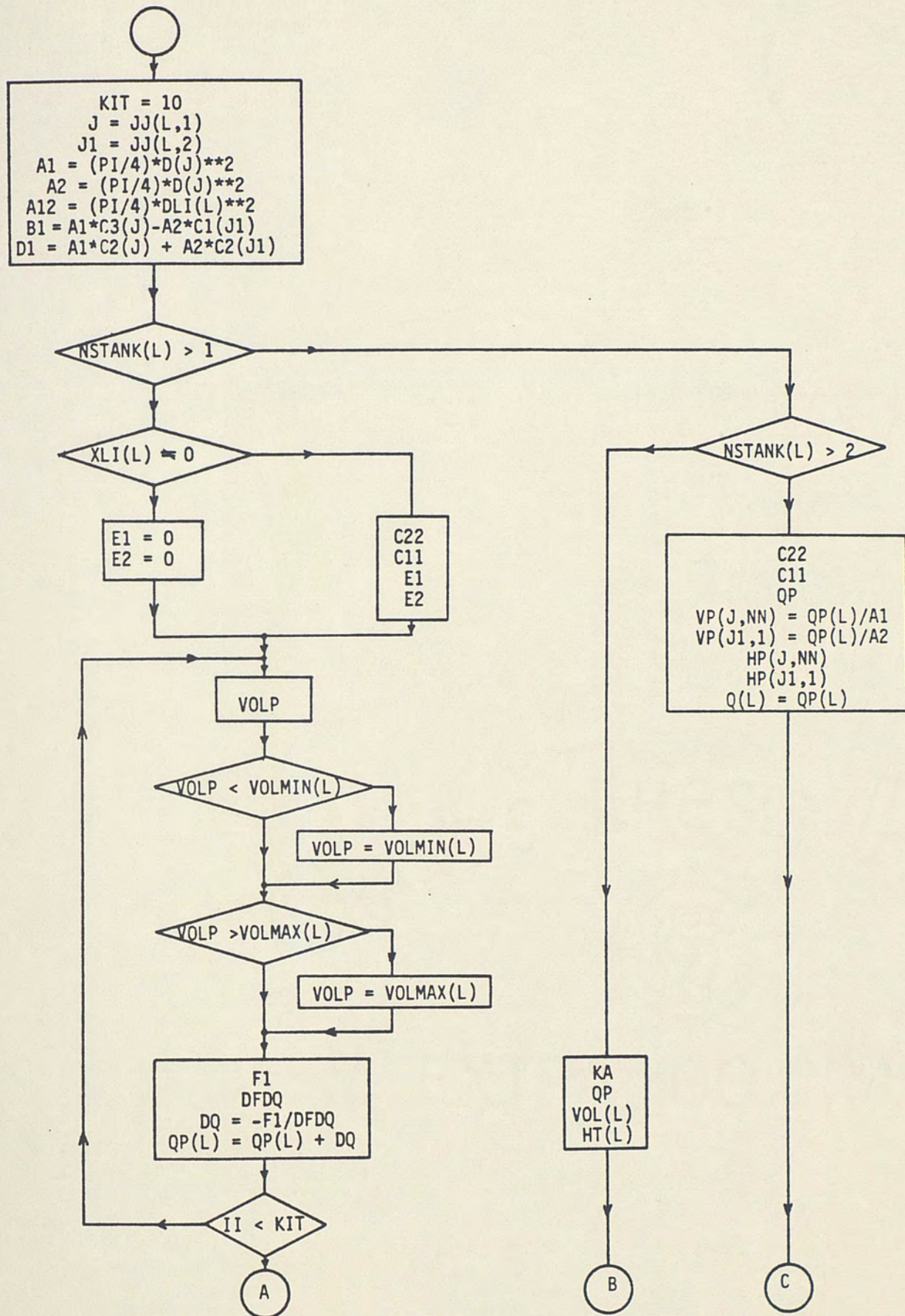


Fig. 23. Flowchart corresponding to new boundaries
(surge tank, lumped inertia and lumped capacitance)

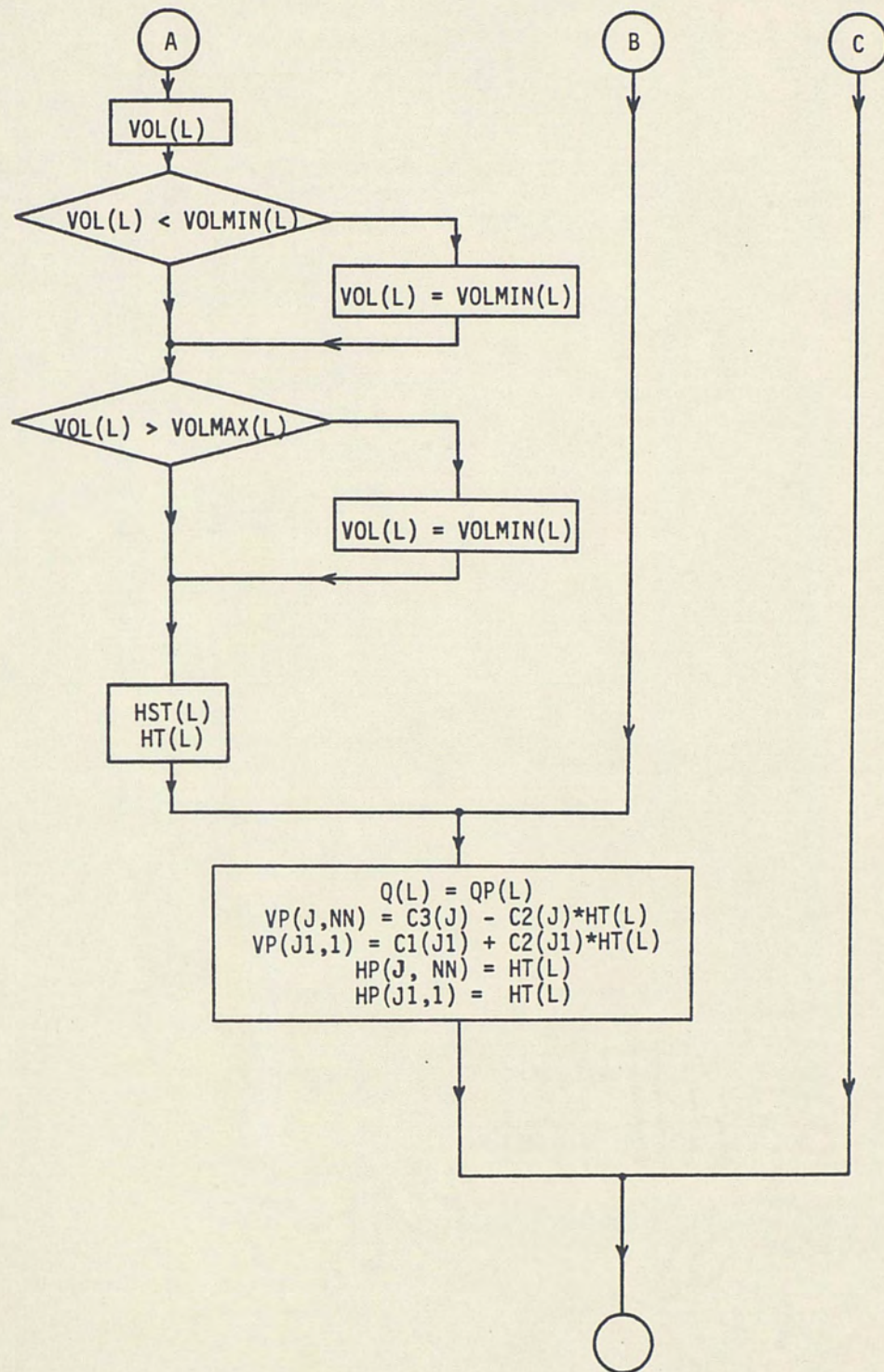


Fig. 23. (Continued)

Liquid Flow with Gas Bubbles

The subroutine PHASE in order to model a flow with the possibility of cavity formation at each reach has been modified.

Cavity formation

When the vapor pressure at any section I becomes lower than vapor pressure, this reach is considered as a boundary where the pressure head is held at vapor pressure. Mathematically the equations are identical to those with a reservoir at the junction with fixed pressure head. Once the pressure has been defined, two different velocities need to be calculated: the upstream velocity V_p using the additional C^+ characteristic equation and the downstream velocity V_{DP} using the C^- characteristic equation (see Appendix A).

The cavity length $X_{CAV,I}$ at section I is set equal to

$$X_{CAV}(I) = \frac{1}{2} (V_{DP} + V_D - V_p - V) \Delta t$$

where V_{DP} and V_p are the down and upstream velocities at time $t + \Delta t$, V_D and V are the down and upstream velocities at time t .

Presence of a Cavity

When at time t a cavity already exists at reach I, the pressure is maintained at vapor pressure, V_p and V_{DP} are calculated as above and the new cavity length $X_{CAV}(I)$ is determined.

Cavity Collapse

When the new cavity length at reach I is found to be negative, the two liquid columns up and downstream of the reach have met, the

cavity length is set equal to 0 and the pressure increase is equal to $(V_P + V - V_{DP} - V_D) \frac{a}{4g}$.

Special care has to be taken in writing the C^+ and C^- characteristic equations. If there is a cavity at section I-1 (or I+1) at time t , V_D (I-1) (or V (I+1)) has to be used instead of V_R (I-1) (or V_S (I+1)) in C^+ (or C^-) equation. This also holds for the determination of $C3(J)$ and $C1(J)$ (corresponding to VCP and VCM) in subroutine STATE where a conditional test has been introduced to select the adequate velocity in the case of a vapor cavity in subsequent sections.

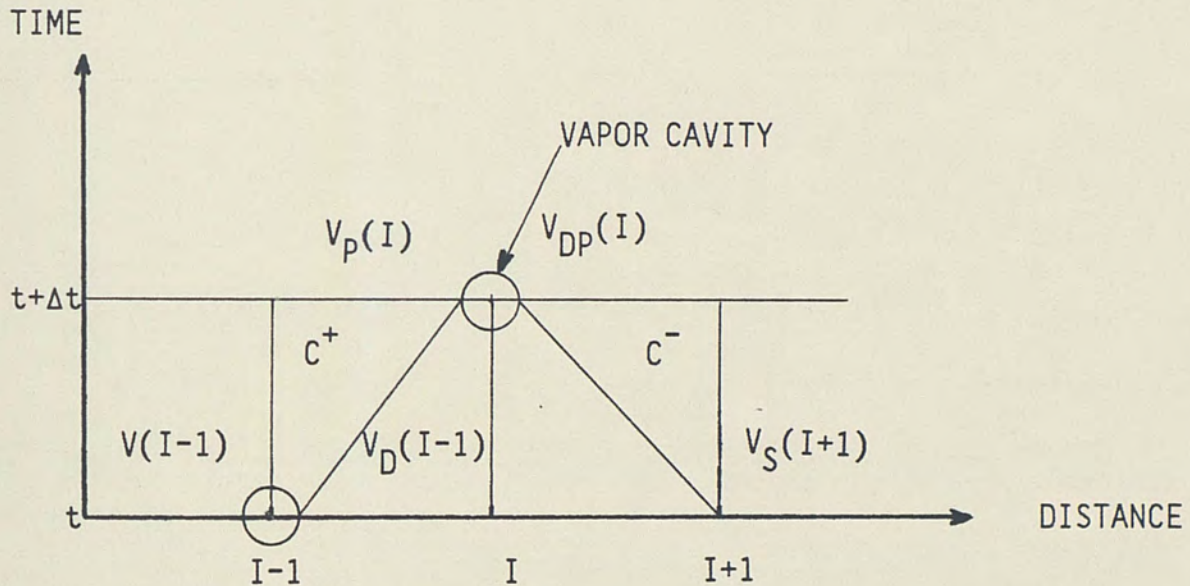


Fig. 24. Creation of a vapor cavity at section I. Upstream (section I-1) the presence of a vapor cavity requires the use of V_D (I-1) in the C^+ characteristic equation. At the downstream section (I+1), since no cavity exists, the extrapolated fluid velocity V_S (I+1) is chosen for the C^- characteristic equation. The pressure at section I at time $t+\Delta t$ is fixed at vapor pressure and two velocities are calculated (V_P (I) and V_{DP} (I)).

At the junctions of two pipes no cavity formation is allowed to form. However when the pressure turns out to be less than vapor pressure, it is set equal to vapor pressure and the velocities calculated in subroutine BOUDRY (for boundary conditions) are conserved. This limitation would have been avoided in the case of an ordinary junction between two pipes, but not in the general case of any junction (union of more than two pipes for example).

For pipe J two output parameters are calculated:

1. the total number of cavities $N_{CAV}(J)$
2. the summation of all the cavities $CAVL(J) = \sum_I X_{CAV,I}$
(total cavity length in pipe J)

NOTE: Since the actual friction losses in pipe J occur only where liquid is present, the friction factor is set

$$FF(J) = F(J) * (XL(J) - L_{CAV}(J)) / XL(J)$$

in which $F(J)$ is the friction factor in pipe J $XL(J)$ is the length of pipe J

If $L_{CAV}(J) > XL(J)$ $FF(J)$ is set equal to 0.

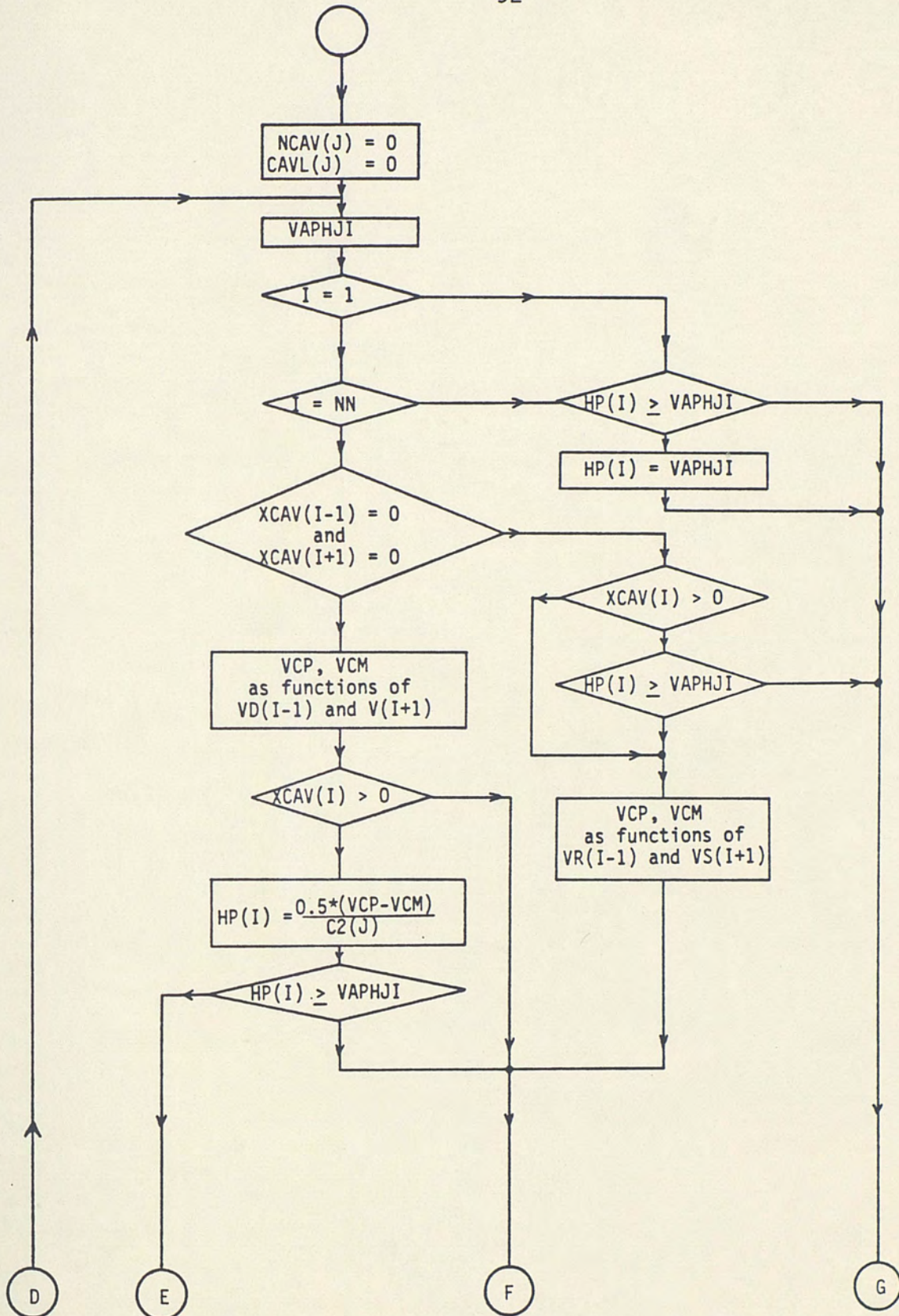


Fig. 25. Flowchart for subroutine PHASE
(flow with vapor cavities)

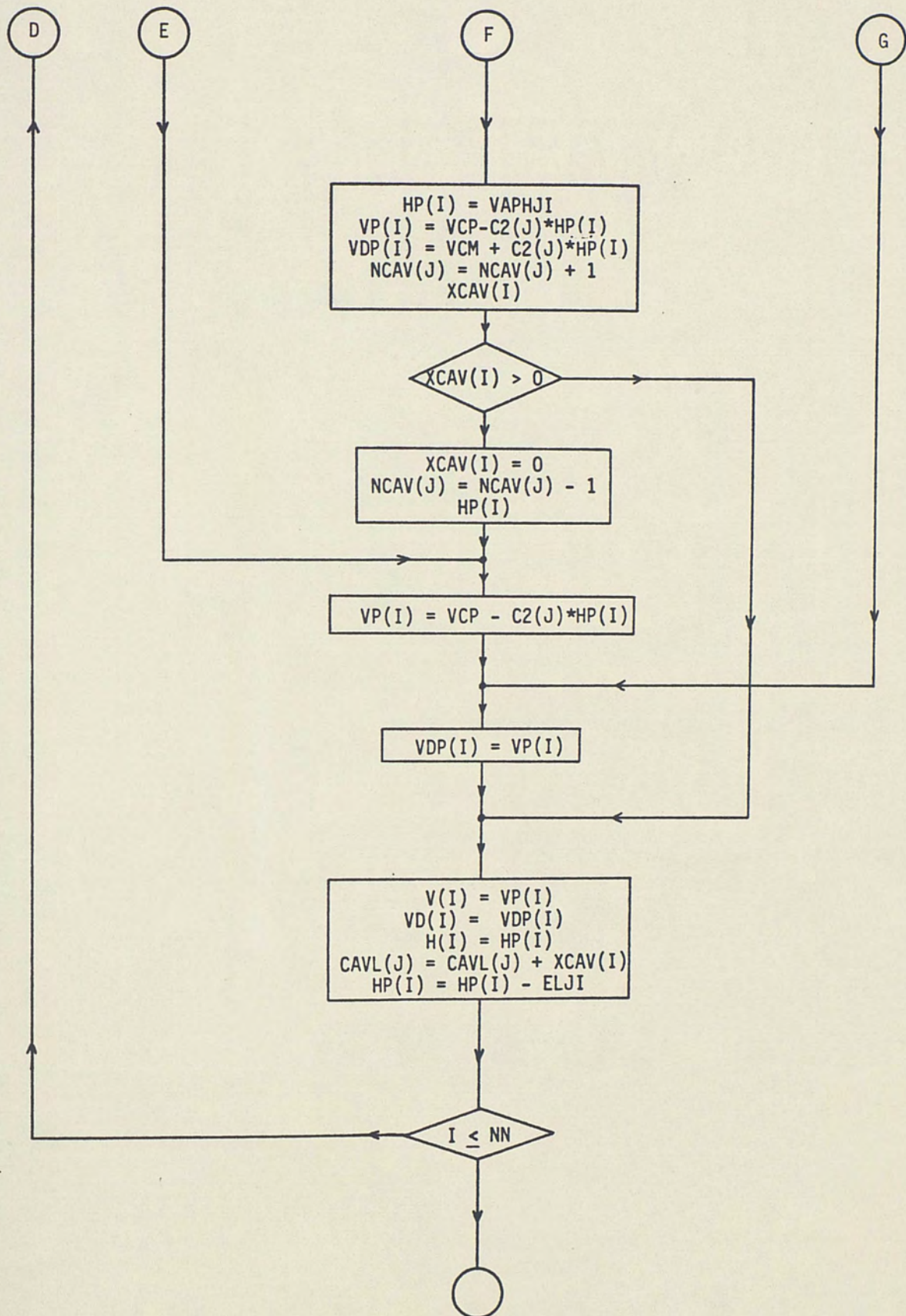


Fig. 25. (Continued)

Output

Due to the changes made to HYTRAN, new variables earned special interest and needed to be outprinted. A new column corresponding to the total cavity length CAVL(J) has been added to the existing pressure head and velocity columns. However since the pressure head in feet of fluid and PSI are always proportional, only the columns giving the pressure in PSI have been kept to earn additional space for the cavity length column.

In case of vapor cavities the variable NCAV(J) has been printed to indicate the number of reaches where a cavity has been permitted to form. This variable is printed right below the line corresponding to the pipe where cavities are present, leaving the line mainly in blank so that the pipes with cavities are easily detectable.

Another useful modification has been the determination of the maximum pressure at any junction occurring between two subsequent outprints. Since three points were of interest (SKID INLET, SKID OUTLET, ORBITER INLET), the program was specialized to print out the maximum values at these three points and the time of occurrence. This addition prevented any missing of a pressure spike occurring at a time when no outprint of the results had been commanded.

Finally in subroutine TMSTEP (routine to check timestep for stability) additional information has been supplemented when the timestep is halved. When the timestep is divided by two, the computer time is doubled and the method of characteristics loses most of its accuracy because of the large interpolation errors. The adequate

reduction of the timestep satisfying the condition of stability is preferable to the drastic timestep halving. Therefore the pipe number where the stability criterium is not fulfilled is indicated to avoid an unnecessary search among all the pipes.

APPENDIX D

SPACE SHUTTLE LIQUID OXYGEN SERVICING SYSTEM

Data were provided by the line data for the LOX servicing system Addendum to the "Selected, thermodynamic and fluid flow data from the Space Shuttle Liquid Oxygen servicing system," by F. N. Lin, W. I. Moore, and S. W. Walker.

Little differences could be noticed between several data sources, namely in the elevation of the main and replenish valves (4 feet difference).

Figure 1 gives a schematic representation of the LOX piping system including the most important points which location and elevation are found in Table 5 and Table 6.

TABLE 5
ELEVATION (IN FEET) OF THE REMARKABLE POINTS FROM FIGURE 1

LOCATION		ELEVATION (feet)
M	SEA LEVEL	0
	E.T. 100% FULL	265.2
	E.T. 0% FULL	222.4
	E.T./ORB	129.6
	GSE/ORB	119.6
	1	95.7
	2	94.7
	3	88.0
	4	88.0
	5	88.0
J	6	85.0
	and 7	85.0
G	A86461	85.0
		85.0
F	and 8	85.0
	9	79.0
E	10	43.5
	11	41.7
	12	13.0
	13	10.7
	A28750	10.7
		10.7
	14	10.7
	15	10.7
	16	10.7
	17	14.0
P		14.0
	18	14.0
O	A196	14.0
	19	14.0
	A134	14.0
T		14.0
	80	10.9
	A57	10.9
	21	10.9
W		11.1
		16.2
	S.T. 100% LEVEL	65.0
	S.T. 73% LEVEL	53.2

TABLE 6

PIPE LENGTH AND INSIDE DIAMETER OF PIPING SECTIONS SHOWN IN FIGURE 1

LOCATION POINTS	DISTANCE (feet)	INSIDE DIAMETER (feet)
E.T. - E.T./ORB	92.5	1.416
E.T./ORB - PV10	12.0	1.416
PV10 - ORIFICE	15.0	0.667
ORIFICE - M	1.5	0.667
M - 1	40.8	0.667
1 - 2	28.6	0.667
2 - 3	5.0	0.667
3 - L	41.0	0.667
L - A86465	3.7	0.667
A86465 - 4	4.5	0.667
4 - 5	3.7	0.5
5 - K	0.7	0.5
K - 6	0.7	0.5
6 - J	18.4	0.5
J - A86461	3.1	0.5
A86461 - G	11.3	0.5
J - A86460	10.3	0.166
A86460 - G	11.0	0.166
G - F	2.3	0.5
F - 7	11.5	0.5
7 - 8	161.2	0.5
8 - 9	12.3	0.5
9 - 10	36.3	0.5
10 - 11	193.0	0.5
11 - 12	166.0	0.5
12 - 13	1006.0	0.5
13 - A28750	21.6	0.5
A28750 - E	14.7	0.5
E - 14	2.2	0.5
14 - 15	14.4	0.5
15 - 16	3.7	0.5
16 - 17	3.7	0.5
17 - P	3.3	0.5
P - 0.43" ORIFICE -	7.0	0.25
P - 1.35" ORIFICE -	20.4	0.25
P - A134 -	3.0	0.5
- 20	3.4	0.5
20 - A57	2.3	0.5
A57 - 21	18.8	0.5
21 - A105	1.0	1.0
A105 - A69	3.2	1.0

TABLE 6 (Continued)

LOCATION POINTS	DISTANCE (feet)	INSIDE DIAMETER (feet)
A 69 - A102	0.5	1.0
A102 - T	5.5	1.0
T - A3	5.4	1.0
A3 - W	21.5	1.0

APPENDIX E

SAMPLE HYTRAN INPUT DATA CALCULATION

In order to apply HYTRAN to the liquid oxygen (LOX) piping system for the case of single phase (liquid) only, a model of the LOX piping system has been made. It derives from the LOX piping system described in Appendix D.

The following simplifications of the LOX piping system were made:

1. Any pipe between two junctions is assumed linear (although the real system may contain bendings).
2. Bendings have been replaced by an equivalent pipe length equal to approximately twice the pipe radius.
3. When two (or more) junctions are close together, they are reduced to one single junction with equivalent properties (C_V value).
4. The pressure gage in the E.T. has been simulated by an extra liquid column height (corresponding to the pressure gage) above the actual liquid level.
5. The storage tank has been simulated by a wide cylinder (since the level remains nearly the same during the analysis time).

The data were obtained on January 24, 1981, when a drain flow was stopped. The drain sequences and data were as follows:

1. After a one-hour stable drain flow the E.T. was at 22% level.
2. The drain rate was $0.103 \text{ m}^3/\text{sec}$, the fluid temperature in a range of -181°C to -180.6°C .
3. A stop drain was initiated by simultaneously commanding the drain valve (A134), the main fill valve (A86461), and the bypass shutoff valve (A196) to close. The closing time was respectively 3.8, 11, and 3.8 seconds.

4. The replenish valve is maintained closed throughout the drain process.
5. The storage tank was vented to the ambient.
6. The E.T. was maintained at a pressure between 36.6 and 50.3 kPa gage.
7. The E.T. has a volume of 543m^3 or 19176 ft^3 .
8. The liquid level in the storage tank is assumed at 73% FULL (EL. 53.2 ft.).

In order to reduce a maximum the computer time, further simplifications have been made.

1. The replenish valve loop has been neglected (since this valve remains closed during the analysis time).
2. The orifice (0.430") in the bypass loop has also been neglected.
3. Some real pipe dimensions have been slightly changed in order to match the requirements of a 6 ft. long reach (smallest length unit).
4. Up to four devices have been combined in one junction (namely the main line drain valve (A102), the flow meter (A69), the drain filter (A105) and the gate valve (A3)).

With these assumptions, the LOX PIPING SYSTEM reduces to the following model containing 22 pipes and 22 junctions (see Figure 3).

Sample Input Data Calculation

From this model several parameters can be obtained directly by only considering Figure 1 (geometry factors):

- NJCT = 22,
- NPIPE = 22,
- NP = 1,2,2,2,2,2,2,2,2,2,2,2,3,2,2,2,3,2,2,2,2,1,
- NSORCE = 1,

- NSINK = 0,0,3,3,0,3,0,1,0,0,0,3,0,1,1,3,0,5,0,3,0,4,
- D = 1.416, 0.667, 0.667, 0.667, 0.667, 0.667, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.25, 0.25, 0.25, 0.5, 0.5, 1.0, 1.0, 30.0,
- XL = 104.5, 6.0, 12.0, 24.9, 91.5, 6.0, 27.0, 186.0, 41.5, 366.0, 1062.5, 7.0, 6.0, 6.0, 6.0, 6.0, 6.0, 6.0, 18.8, 9.7, 27.0, 37.0,
- ALPHA is easily calculated as seen in Figure 26.

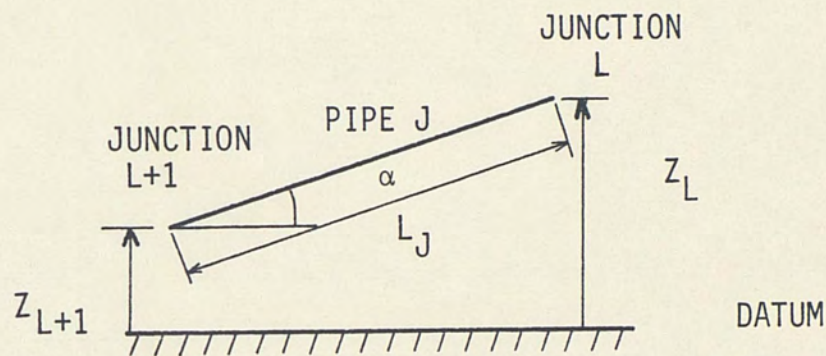


Fig. 26. Determination of the variable ALPHA (α).

$$\sin \alpha = \frac{Z_{L+1} - Z_L}{L_J}$$

$$\text{or } \alpha = \sin^{-1} \left(\frac{Z_{L+1} - Z_L}{L_J} \right)$$

- ALPHA = -68.31, -18.46, -18.46, -90.0, -4.2, 0.0, -6.38, 0.0, -90.0, -4.78, -0.124, 28.13, 0.0, 0.0, 0.0, 0.0, 0.0, -30.0, 0.0, 0.0, 11.1, 90.0,
- JJ = 1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 14, 18, 19, 20, 21, 22, 8*0, 0, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 0, 8*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 15, 0, 0, 0, 17,
- IC = -1, 8*0, 0, -1, 0, 8*0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 1,
- ELEV = 222.4, 125.3, 123.4, 119.6, 94.7, 88.0, 88.0, 85.0, 85.0, 43.5, 13.0, 10.7, 14.0, 14.0, 14.0, 14.0, 14.0, 11.0, 11.0, 11.0, 16.2, 53.2,

N is defined once the length of the reaches is fixed. Choosing the basic reach length as 6 ft. H is then the pipe length divided by the reach length.

- $N = 17, 1, 2, 4, 15, 1, 4, 31, 7, 61, 177, 1, 1, 1, 1, 1, 1, 1, 3, 1, 4, 6,$

The other parameters are dependent on the liquid properties, and the drain conditions.

The liquid oxygen density at the given temperature range is assumed to be

- $\text{RHO} = 71.3 \text{ lb/ft}^3$

The sonic velocity can be assumed 2900 ft/sec in the cross-country line, 2000 ft/sec in the flex hose section and 2600 ft/sec anywhere else in the system (due to presence of bends)

- $A = 3 * 2600., 2000., 5 * 2600., 2 * 2900., 11 * 2600.,$

Assuming that the E.T. is a vertical cylinder of height equal to $Z(100\%) - Z(1) = 42.8$ ft. yields

-

$$XHIG2 = 42.8 \text{ ft.}$$

Knowing the total volume of the E.T. (19176 ft^3) yields its radius

- $RADTK_1 = 11.95 \text{ ft.}$

Since the pressure gage in the E.T. is maintained in the range of 36.6 to 50.3 k Pa gage, the assumption of 50 k Pa gage yields a column height of 14.7 ft. (liquid oxygen).

When E.T. is 22% full, the liquid level is approximately at elevation 232 ft.

Finally adding the pressure gage to this level yields an equivalent liquid level elevation of 246.7 ft. so

- $XHIGH1 = 18.5 \text{ ft.}$
- $ITANK1 = 2$ (vertical cylindrical tank)

The initial drain conditions are obtained from the flow rate ($0.103 \text{ m}^3/\text{sec}$) or $3.637 \text{ ft}^3/\text{sec}$

This datum yields directly the initial velocities in the pipes with the knowledge of their respective diameters (except in the bypass loop, where supplementary calculations are necessary as detailed in the Addendum at the end of this Appendix.

- $VO = 2.307, 10.42, 10.42, 10.42, 10.42, 10.42, 18.52, 18.52, 18.52, 18.52, 18.52, 17.90, 17.90, 17.90, 2.47, 2.47, 18.52, 18.52, 4.63, 4.63, 0.005,$

In the Addendum to the "Selected thermodynamic and fluid flow data from Space Shuttle Liquid Oxygen servicing system" the C_v values are given for the valves, filters, flow meters... Using the relationship between C_{44} and C_v derived in Appendix B, the parameter C_{44} can be calculated (sonic velocity and pipe diameter are known at each junction).

NOTE: The equivalent value of C_{44} corresponding to several devices put in series at one junction having each a C_v value is obtained noticing that the head loss across one device is

$$\Delta H = \frac{\alpha}{C_{44}}$$

where $\alpha = 0.0503 \frac{q_a^2}{D_J^4}$ is a constant (see Appendix B).

$$\text{For } N \text{ devices } (\Delta H)_{\text{tot}} = \sum_{i=1} \frac{\alpha}{C_{44 i}} = \alpha \left(\frac{1}{C_{44 1}} + \frac{1}{C_{44 2}} + \dots + \frac{1}{C_{44 N}} \right)$$

$$\text{the equivalent } (C_{44})_{\text{eq.}} \text{ is then } (\Delta H)_{\text{tot}} = \frac{\alpha}{C_{44 \text{ eq.}}}$$

Equating both right-hand sides of the equations yields

$$\frac{1}{C_{44 \text{ eq.}}} = \frac{1}{C_{44 1}} + \frac{1}{C_{44 2}} + \dots + \frac{1}{C_{44 N}}$$

The C_{44} values at the different junctions where head loss is considered are:

$$\begin{array}{lll} 3 : & C_v = 3500 & (\text{PV } 10) \quad C_{44} = 17463 \\ 4 : & (C_v)_1 = 3500 & (\text{PV}(C_{44})_1 = 17463 \end{array}$$

$$(C)_2 = 1.03 \quad (\text{ORIFICE: } 4.75") \quad (C_{44})_2 = 686 \quad C_{44} = 660$$

$$(\text{See: CRANE, (1965)} \quad \frac{D_o}{D_1} = 0.60)$$

6 :	$C_v = 1800$	(A86465)	$C_{44} = 4620$
8 :	$C_v = 2000$	(A86461)	$C_{44} = 18020$
12 :	$C_v = 2700$	(A28750)	$C_{44} = 32843$
14 :	$C_v = 2000$	(A134)	$C_{44} = 18020$
15 :	$C_v = 500$	(A196)	$C_{44} = 18020$
16 :	$C = 1.00$	(ORIFICE 1.35")	$C_{44} = 213$

$$(\text{See: CRANE, (1965)} \quad \frac{D_o}{D_1} = 0.45)$$

18 :	$C_v = 850$	(A57)	$C_{44} = 3255$
20 :	$(C_v)_1 = 3000$	(A105)	$(C_{44})_1 = 2534$
	$(C_v)_2 = 6400$	(A69)	$(C_{44})_2 = 11533$
	$(C_v)_3 = 9000$	(A102)	$(C_{44})_3 = 22808$
	$(C_v)_4 = 11000$	(A3)	$(C_{44})_4 = 34071$
22 :			$C_{44} = 7172$

- $C_{44} = 0., 0., 17463., 660., 0., 4620., 0., 18020., 0., 0.,$
 $0., 32843., 0., 18020., 18020., 213., 0., 3255., 0., 1804.,$
 $0., 7172.,$

- HT is the initial head at each junction (in feet). The values at junction 1 and 22 are respectively

$$HT(1) = ELEV(1) + (XHIG2 - XHIGH1) = 246.7 \text{ ft.}$$

$$HT(22) = ELEV(22) = 53.2 \text{ ft.}$$

The total piping system head loss $(HT(1) - HT(22)) = 193.5 \text{ ft.}$, the knowledge of the flow rate "q" and the head losses at each junction, leads to the determination of the friction factor "f." Once "f" has been determined HT can be evaluated at each junction.

- The friction losses in the pipes are $\Delta H = 0.02517 \frac{fLq^2}{D^5}$
(where f is still an unknown parameter)
- The losses at the junctions $\Delta H = 0.0503 \frac{a q^2}{C_{44} D^5}$
(which are known values).

TABLE 7
INITIAL PRESSURE HEADS AT THE JUNCTIONS

No. of junction	No. of pipe	pipe length L	pipe diameter D	C_{44}	ΔH (ft) junction	$\Delta H/f$ (ft) pipe	HT (ft)
1	1	104.5	1.416			6.08	246.7
2	2	6.0	0.667			15.17	246.7
3	3	12.0	0.667	17463	0.50	37.83	246.2
4	4	24.9	0.667	660	13.27	62.80	232.6
5	5	91.5	0.667			230.76	232.0
6	6	6.0	0.667	4620	1.89	15.13	228.1
7	7	27.0	0.5			287.66	228.0
8	8	186.0	0.5	18020	1.54	1981.67	223.9
9	9	41.5	0.5			442.15	206.5
10	10	366.0	0.5			3899.43	202.6
11	11	1062.5	0.5			11320.06	168.4
12	12	7.0	0.5	32843	0.84	74.58	68.0
13	13	6.0	0.5				67.4
14	14	6.0	0.5	18020	1.47	} 2.39	66.9
15	15	6.0	0.25	18020	0.01		67.3
16	16	6.0	0.25	213	2.39		65.0
17	17	6.0	0.25				65.0
18	18	6.0	0.5	3255	8.50	63.92	55.9
19	19	18.8	0.5			200.30	54.1

TABLE 7 (Continued)

No. of junc- tion	No. of pipe	pipe length L	pipe diameter D	C_{44}	ΔH (ft) junction	$\Delta H/f$ (ft) pipe	HT (ft)
20	20	9.7	1.0	1804	0.96	3.23	53.2
21	21	27.0	1.0			9.00	53.2
22		37.0	30.0	7172	$\frac{0.00}{29.83}$	0	53.2
						<u>18649.77</u>	

The above table gathers the losses of both kinds in the whole piping system:

Summing up all the losses yields

$$193.5 = 29.89 + 18649.77 f.$$

or $f = 0.0088$

- $F = 0.0088$

NOTE: This value is rather small, corresponding to a smooth pipe.

HT at junction L+1 is found by subtracting the losses occurring between junctions L and L+1 to the value of HT at junction L (see Table 7).

- HT = 246.7, 246.7, 246.2, 232.6, 232.0, 228.1, 228.0, 223.9, 206.5, 202.6, 168.4, 68.0, 67.4, 66.9, 67.3, 65.0, 65.0, 55.9, 54.1, 53.2, 53.2, 53.2,
- C3P = 246.7, which is equal to the value of HT at junction 1 .

The valves closing parameters NTAU, TIME, and TAUU are non-zero values only for junctions 8 , 14 , and 15 . Ten points are chosen for each valve (values of TAUU are taken from Appendix B, Fig. 16. Butterfly curve).

- NTAU = 0, 0, 0, 0, 0, 0, 0, 10, 0, 0, 0, 0, 0, 10, 10,
- TIME = 70*0., 0., 2.2, 3.3, 4.4, 5.5, 6.6, 7.7, 8.8, 9.9, 11.0,
50*0., 0., 0.76, 1.14, 1.52, 1.9, 2.28, 2.66, 3.04,
3.42, 3.8, 0., 0.76, 1.14, 1.52, 1.9, 2.28, 2.66, 3.04,
3.42, 3.8,
- TAUU = 70*0., 1.0, 0.69, 0.53, 0.42, 0.29, 0.19, 0.12, 0.05,
0.01, 0.0,
50*0., 1.0, 0.69, 0.53, 0.42, 0.29, 0.19, 0.12, 0.05,
0.01, 0.0, 1.0, 0.69, 0.53, 0.42, 0.29, 0.19,
0.12, 0.05, 0.01, 0.0,

DELT has to be less than the reach length divided by (sonic speed + initial fluid velocity).

- $\text{DELT} \leq \frac{6}{2900 + 18.5} \text{ sec.}$
- $\text{DELT} = 0.002 \text{ sec.}$
- $\text{TMAX} = 4.5 \text{ sec.}$ since the pressure spikes occur at 3.8-4.5 sec.

The output parameters are chosen as follows:

From time t =	0 sec to t = 2.5 sec	print each 0.5 sec
	t = 2.5 sec to t = 3.6 sec	0.2 sec
	t = 3.6 sec to t = 4.5 sec	0.05 sec

- $\text{LPRT} = 1$
- $\text{ITPRNT} = 250$
- $\text{TIME2} = 2.5$
- $\text{ITPR2} = 100$
- $\text{TIME3} = 3.6$
- $\text{ITPR3} = 25$

COMMENT 1

Since the number of reaches in some pipes exceeded 40, the array dimension of several variables had to be changed in HYTRAN, namely, V, H, VS, HS, VR, HR, VP, HP, VPP, XCAV. In these two-dimensional variables, only the second array (column corresponding to the dummy variable I) had to be modified to 200 (maximum number of reaches).

COMMENT 2

This model requires a computer time less than 15 minutes. As indicated before, several devices have been combined at some junctions, but the general piping system shape has been respected (orientation and distribution of the pipes in a vertical plane).

Another model had previously been made. That first model was a detailed version of the piping system (devices kept separate at

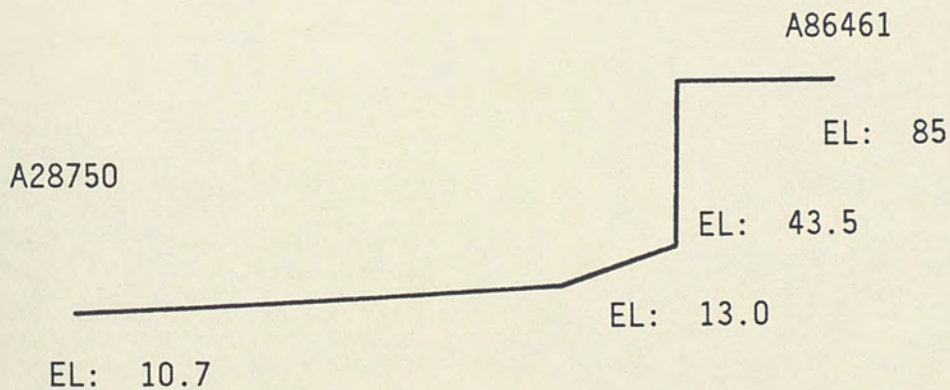
their actual location). This constraint required a smaller reach length (3 ft. instead of 6 ft. in the second model) and yielded a larger number of pipes than for the second model exposed before.

However the real orientation of the pipes in a vertical plane has not been respected.

As an example, the four pipes numbered 8, 3, 10, and 11 from the second model had been approximated by a single pipe of length equal to the sum of the four pipe lengths, both end elevations coinciding however with the actual junction (valves) elevation. ALPHA was calculated as indicated below.



1st Model (Elevations are given in feet)



2nd Model

Fig. 27. Difference in pipe orientation between 1st and 2nd model.

The first model consisted of 27 pipes and 25 junctions.

The CPU time was about 3 hours 30 minutes. This large computer time led to the second model exposed above, with a computer time of less than 5 minutes. The results (pressure and velocity at the junctions) are similar, (see Figures) indicating that the approximations made in the second model were justified. An even simpler model could have been considered, in which pipes 8, 9, 10, and 11 would have been replaced by a single pipe as in the first model.

COMMENT 3

In this sample calculation C_{44} constants have been calculated by hand. A lately HYTRAN code modification (see Appendix C) avoids this tedious calculation and C_v constants can readily be used as input data.

ADDENDUM

Initial Velocities in the Bypass Loop.

This part of the piping system consists of two parallel branches. The total head losses across each branch have to be equal. Two kinds of losses are considered (for derivation, see Appendix B).

- friction losses in the pipes	$\rightarrow \Delta H = 0.02517 \frac{f L q^2}{D^5}$
	<hr style="width: 50%; margin: 0 auto;"/>
- head losses at the junctions (valves, orifice)	$\rightarrow \Delta H = 0.0503 \frac{a q^2}{C_{44}^2 D^4}$

First branch

$$\Delta H_{\text{tot}} = 0.02517 \frac{f q_1^2}{D_{13}^5} (L_{13} + L_{14}) + 0.0503 \frac{a q_1^2}{(C_{44})_{14}^2 D_{13}^4}$$

Second branch

$$\Delta H_{\text{tot}} = 0.02517 \frac{f q_2^2}{D_{15}^5} (L_{15} + L_{16} + L_{17}) + 0.0503 \frac{a q_2^2}{D_{15}^4} \left(\frac{1}{(C_{44})_{15}^2} + \frac{1}{(C_{44})_{16}^2} \right)$$

Equating the right-hand side of both equations yields a relationship between q_1 and q_2 .

Assuming f to be equal to 0.008 yields:

$$\left(\frac{0.02517 (0.008)}{(0.5)^5} (12) + \frac{0.0503 (2600)}{18020 (0.5)^4} \right) q_1^2 = \left(\frac{0.02517 (0.008)}{(0.25)^5} (18) + \right. \\ \left. \frac{0.0503 (2600)}{(0.25)^4} \left(\frac{1}{18020} + \frac{1}{213} \right) \right) q_2^2$$

$$0.193 q_1^2 = 162.477 q_2^2$$

or

$$\underline{0.44 q_1 = 12.75 q_2}$$

Another relationship between q_1 and q_2 is

$$\underline{q_1 + q_2 = q = 3.637 \text{ ft}^3/\text{sec.}}$$

Solving for q_1 and q_2 yields

$$q_1 = 3.516 \text{ ft}^3/\text{sec.}$$

$$q_2 = 0.127 \text{ ft}^3/\text{sec.}$$

Thus the initial velocities are found to be:

$$\text{First branch: } \underline{V_0 = 17.90 \text{ ft/s.}}$$

$$\text{Second branch: } \underline{V_0 = 2.47 \text{ ft/s.}}$$

And the total head loss between junctions 12 and 17 is:

$$\Delta H_{\text{tot}} = 2.39 \text{ ft.}$$

APPENDIX F

ONE-PHASE FLOW PARAMETRIC STUDY

For the case of the one-phase flow a parametric study was conducted in order to get a better insight in the fluid pressure behavior and to identify the most influent parameters. Basically all the characteristics of the system and properties of the fluid have been treated as variables, changing one parameter at the time and leaving all others constant. The results are visually presented in Figures 28 to 44 at the end of this Appendix.

The following comments may be made:

1. The measured skid inlet pressure was higher than all theoretical predictions.
2. The timing was in good agreement with the experiment.
3. Only the introduction of some elastic section (lumped capacitance (Figures 40 and 41) air chamber (Figure 28) or very low sonic velocity (Figure 31)) between the skid inlet and the E.T. yield a wide single pressure peak instead of two narrow ones. This is actually justified by the presence of the TMS vent line which contains vapor and the 20-foot-long flexhose located between skid outlet and orbiter inlet.
4. The second pressure spike is due to the reflection at the E.T. and is highly dependent on the distance between the

measurement point to E.T. This is shown in Figures 34, 35, and 36. A change in pipe length downstream the skid inlet has no significant influence on the shape of the pressure spikes, but the same change between skid inlet and E.T. modifies considerably the peak amplitude of the first spike (50% increase) and reduces the second peak.

5. The valve closure time is obviously an important parameter. A reduction by half increases the pressure spike amplitude by 50% (Figure 37).
6. The sonic velocity has a double influence: it determines the occurrence of the pressure spike and its magnitude. As exposed in Chapter 1 the amplitude of the pressure spike is proportional to the sonic velocity and Figures 32 and 33 confirm this observation.
7. The surge tank and the lumped inertia containing both an inertia element tend to accentuate the second peak magnitude. An interesting effect of a lumped inertia is the increase of the peak magnitude downstream and decrease of the peak magnitude upstream the element. When inserted between skid inlet and outlet, a lumped inertia separates the curves as it is shown on the experimental curve increasing the skid inlet and decreasing the skid outlet maximum.
8. Of lesser influence on the peak maximum and curve shape is the valve constant C_v and the friction factor. Both modify

the steady state conditions but almost not the transient pressures (less than 2-3%).

9. Of negligible influence is the piping model. A horizontal pipe connected to a vertical one can be replaced by one single pipe of length the sum of both pipes connected between the two extreme points of the two previous pipes. Various valves located in close vicinity from one another can also be substituted by a single valve provided an equivalent C_V coefficient is given to that valve.
10. Substituting a cylindrical tank by a pipe of diameter equal to the tank diameter yields the same results.
11. A change in the fluid density does not affect the pressure head increase but only the pressure (in psig) since the latter is directly proportional to the density and the pressure head.

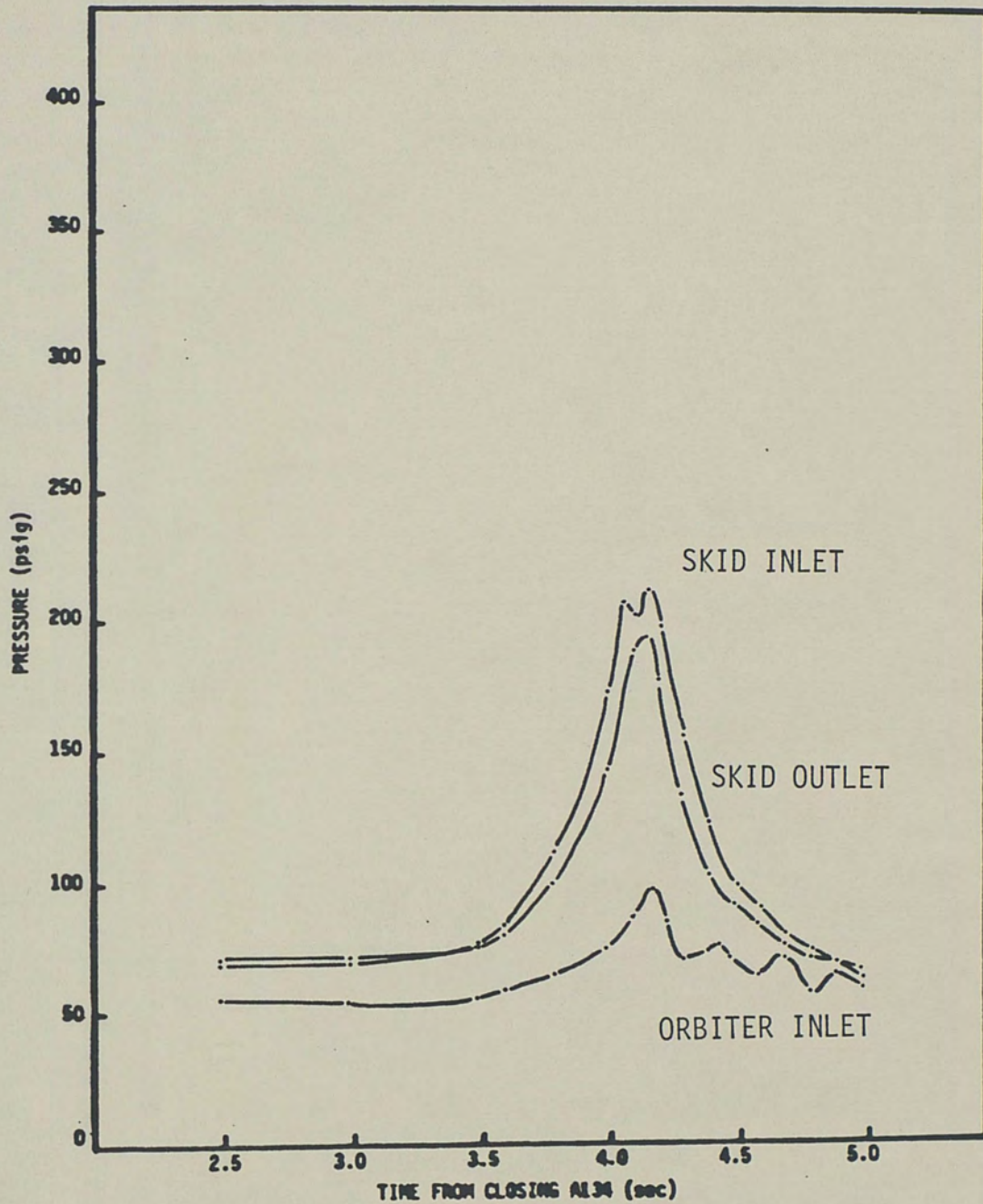


Fig. 28. Effect of a vapor chamber between skid inlet and skid outlet. The introduction of a vapor chamber between skid inlet and outlet damps out. The secondary pressure peaks at the skid outlet as it appears on the measured recordings.

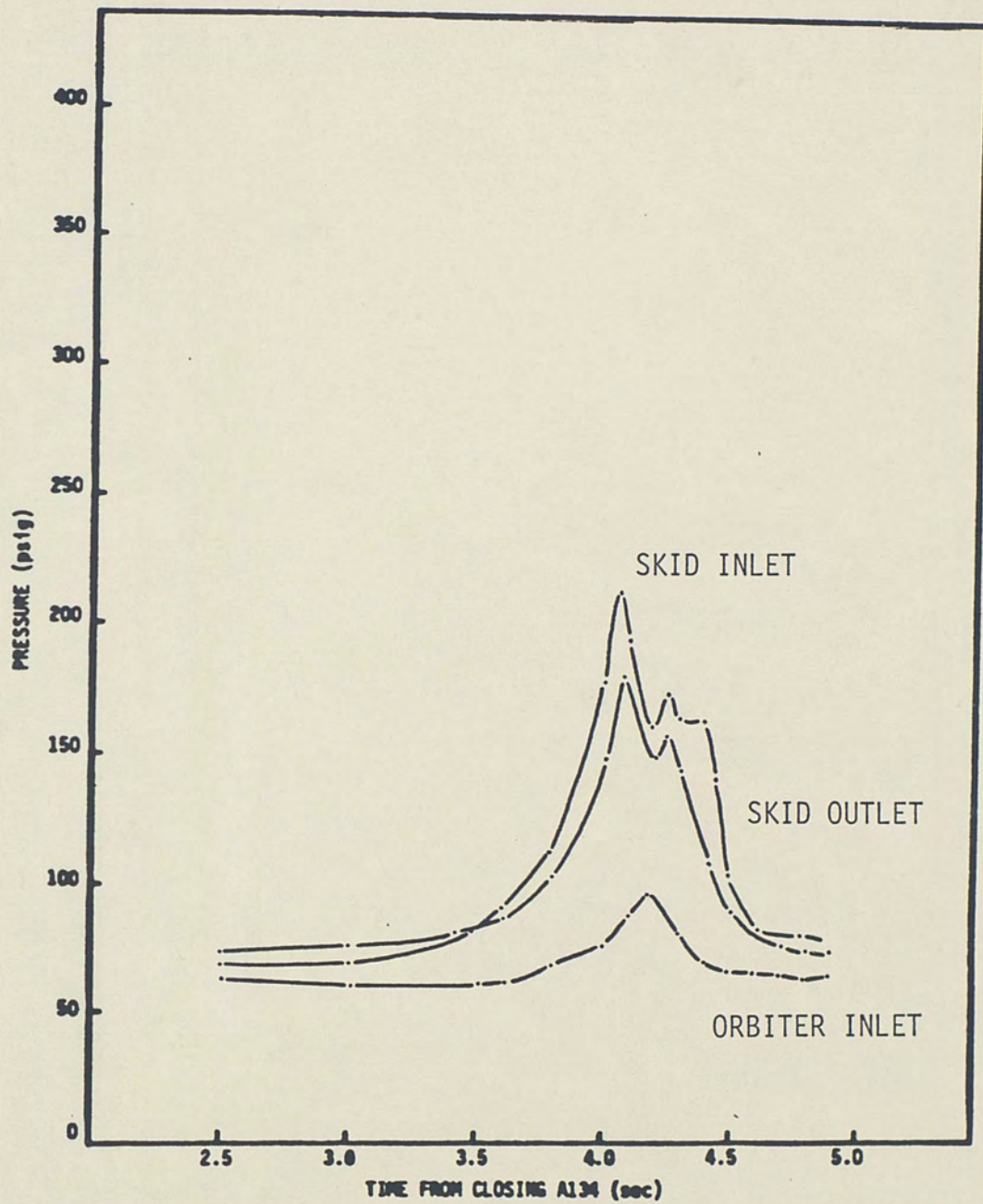


Fig. 29. Simulation of T.S.M. vent line by a vapor accumulator. The introduction of a vapor chamber simulating the T.S.M. vent line damps all secondary pressure peaks out at the orbiter inlet as it appears in the measured recordings.

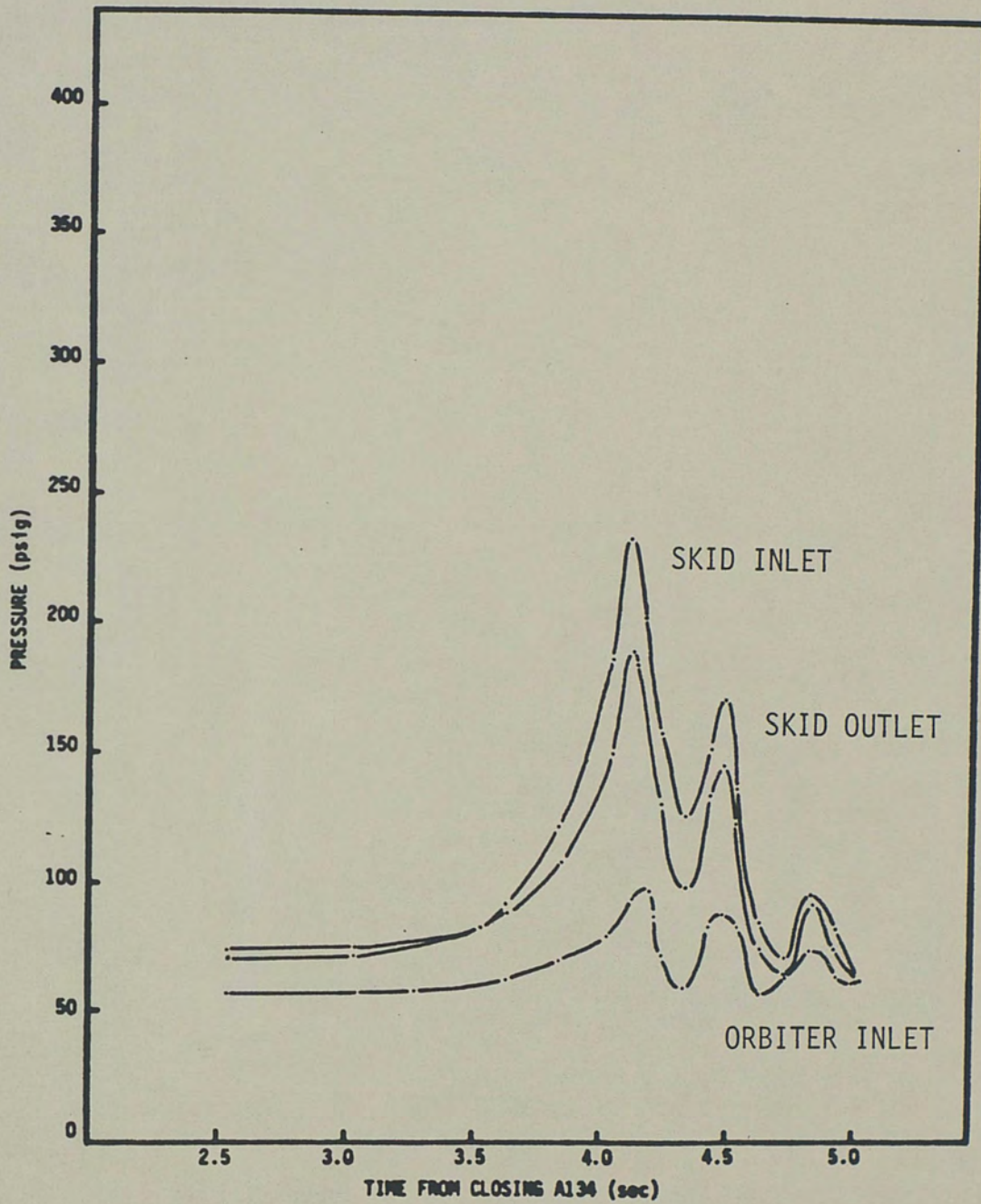


Fig. 30. Absence of any vapor accumulator. In the absence of vapor chambers, high secondary pressure spikes due to multiple reflections at the boundaries (S.T.) and (E.T.) are created.

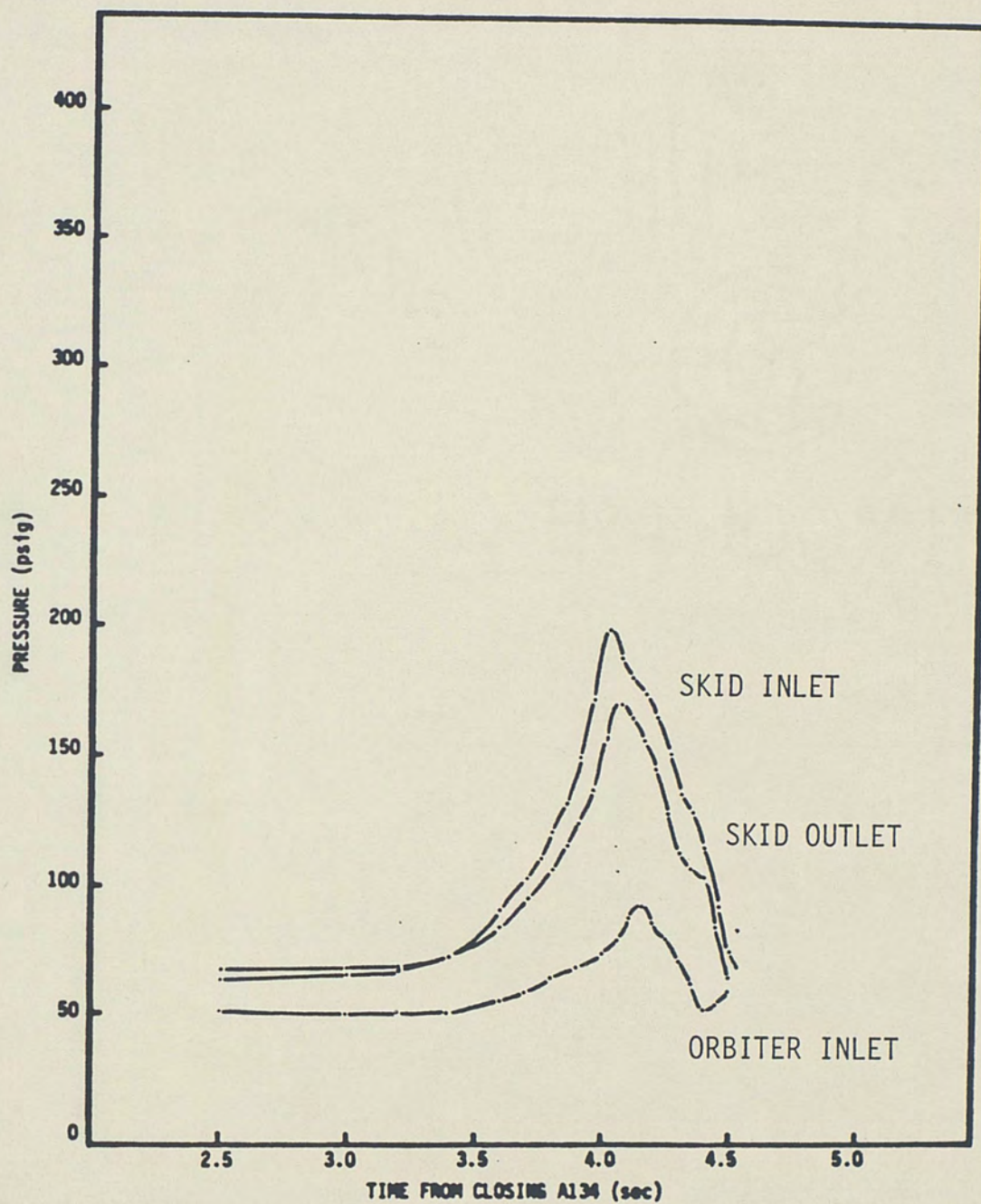


Fig. 31. Effect of sonic velocity ($a = 1000$ ft/sec). Setting the sonic velocity to 1000 ft/sec in pipeline between orbiter inlet and E.T. damps out the secondary pressure peaks (no vapor chamber in the system).

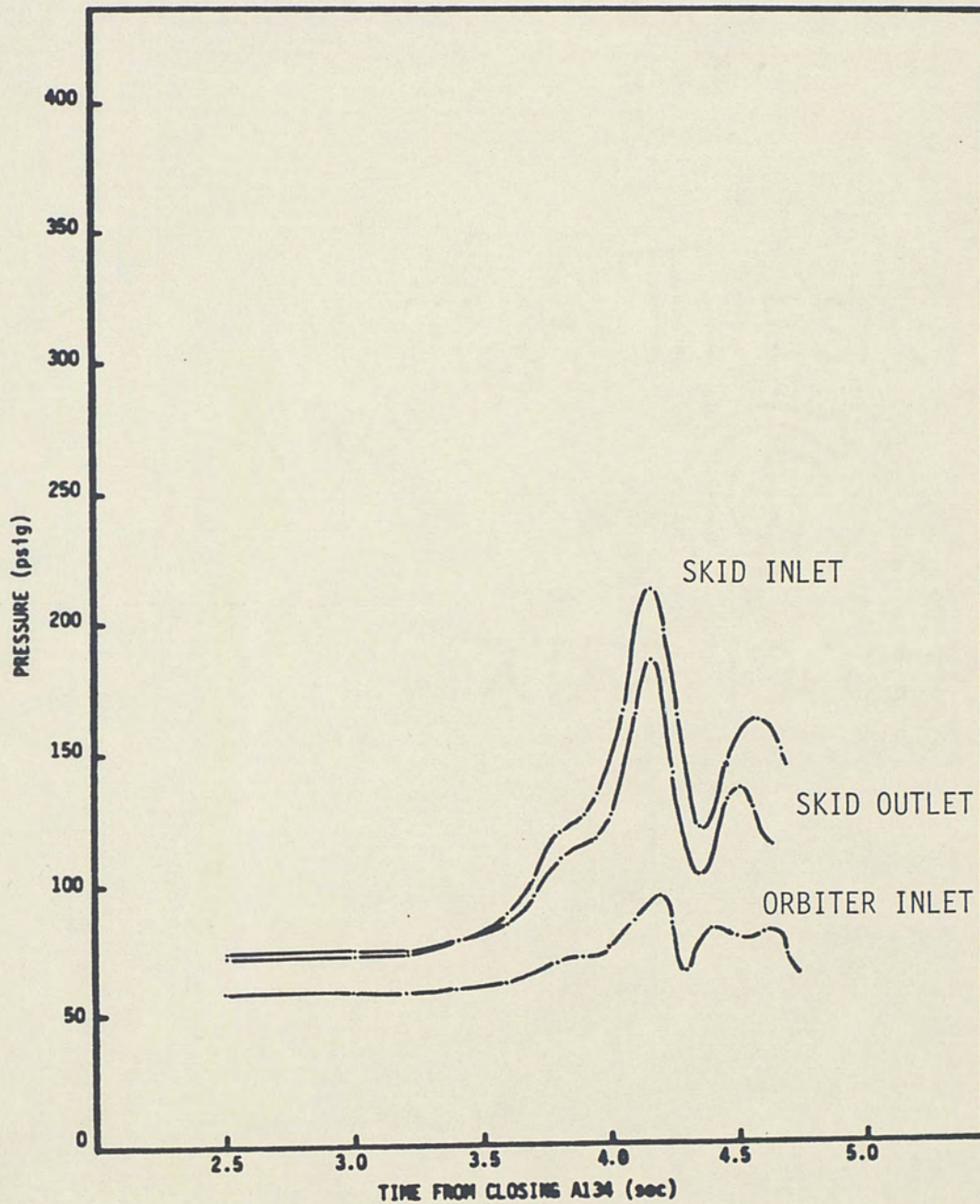


Fig. 32. Effect of sonic velocity ($a = 2300$ ft/sec). A reduction of the sonic velocity ($a = 2300$ ft/sec) delays the pressure spikes at all three measure points (no vapor chamber in the system).

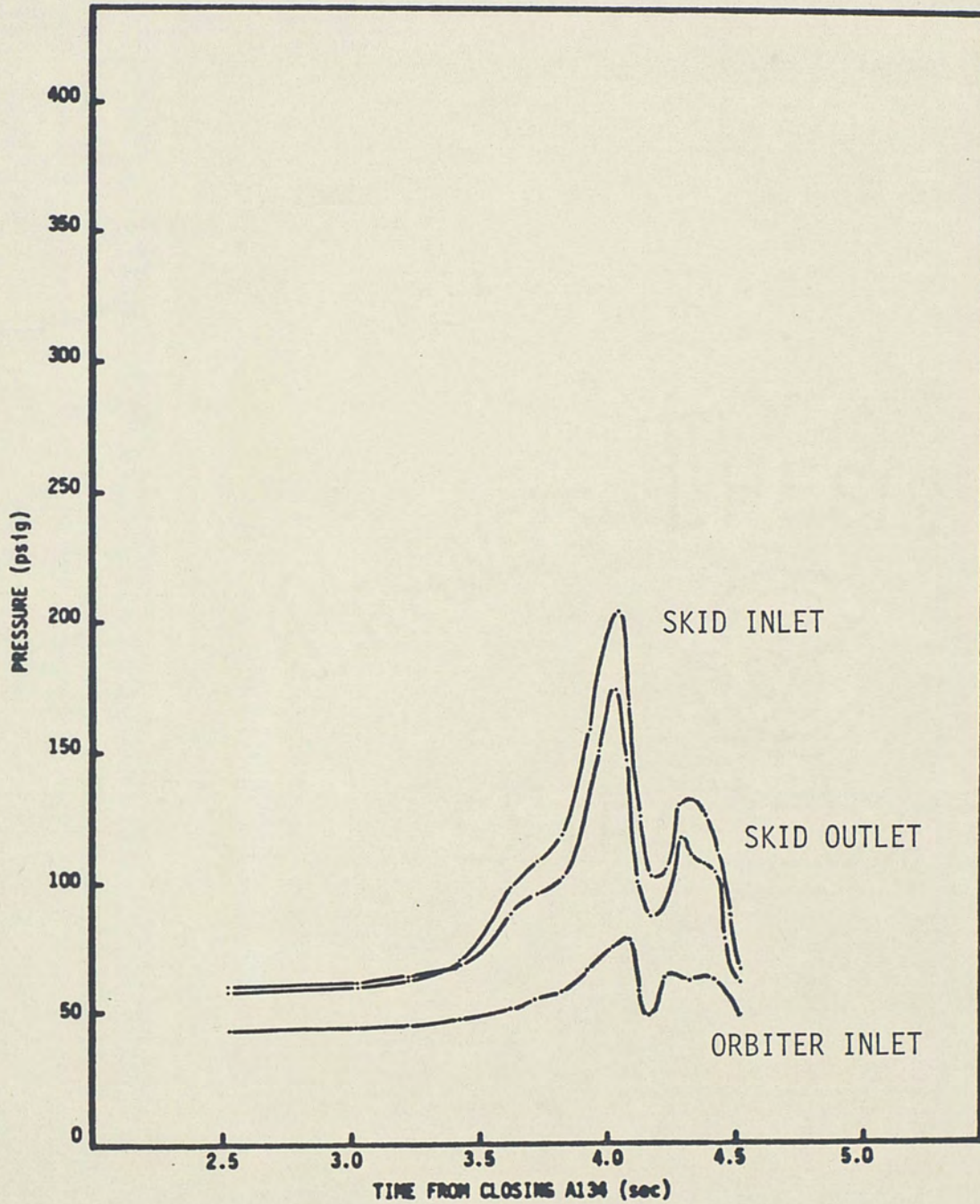


Fig. 33. Effect of sonic velocity ($a = 2900$ ft/sec). Constant wavespeed corresponding to sonic velocity in infinite fluid ($a = 2900$ ft/sec). Same comments as in figure 32.

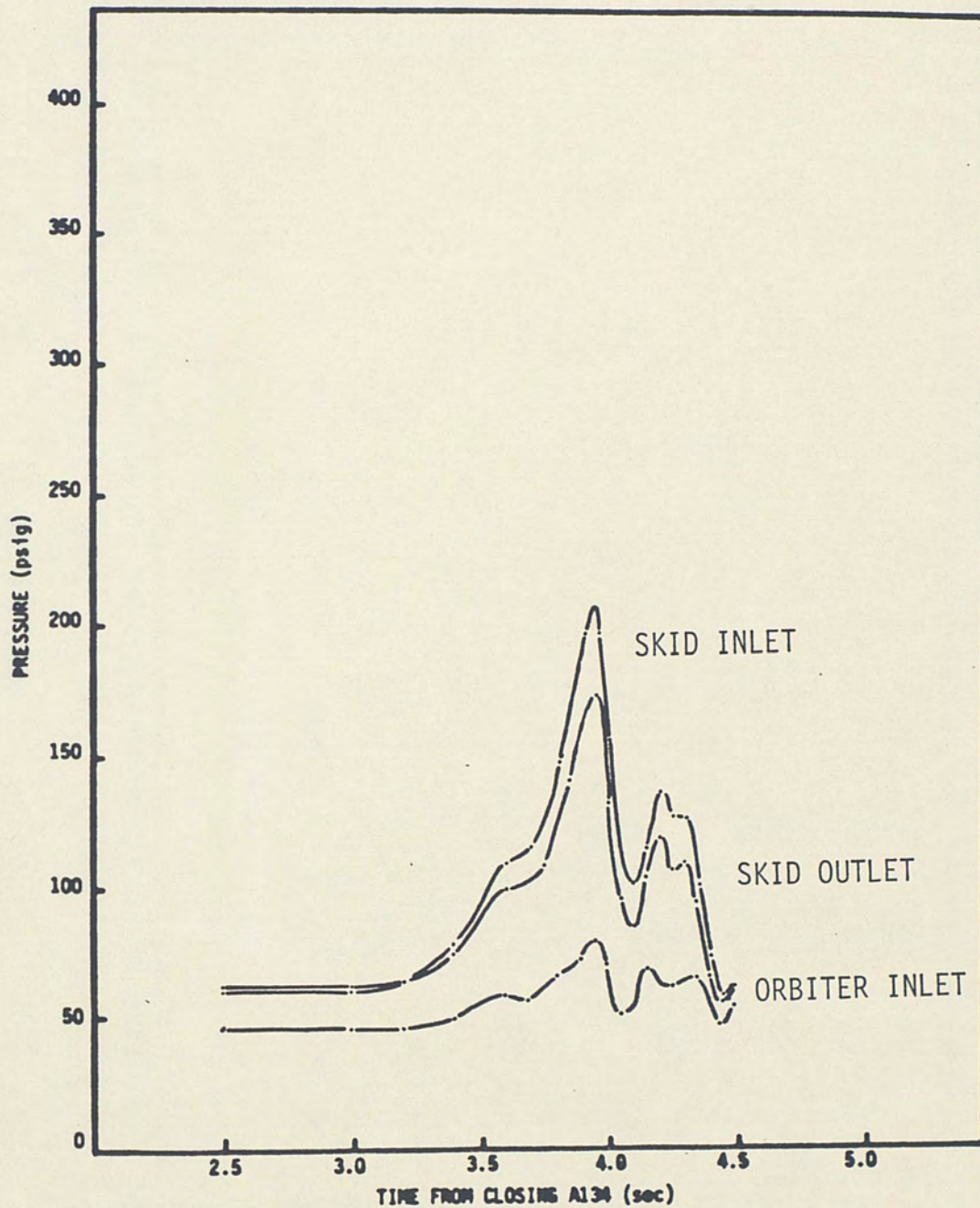


Fig. 34. Effect of the system geometry (reduction in length of the cross country line). A 200 ft reduction in length of the cross country line has little influence on pressure spikes (small advance in time) ($a = 2900$ ft/sec, no vapor chamber in the system).

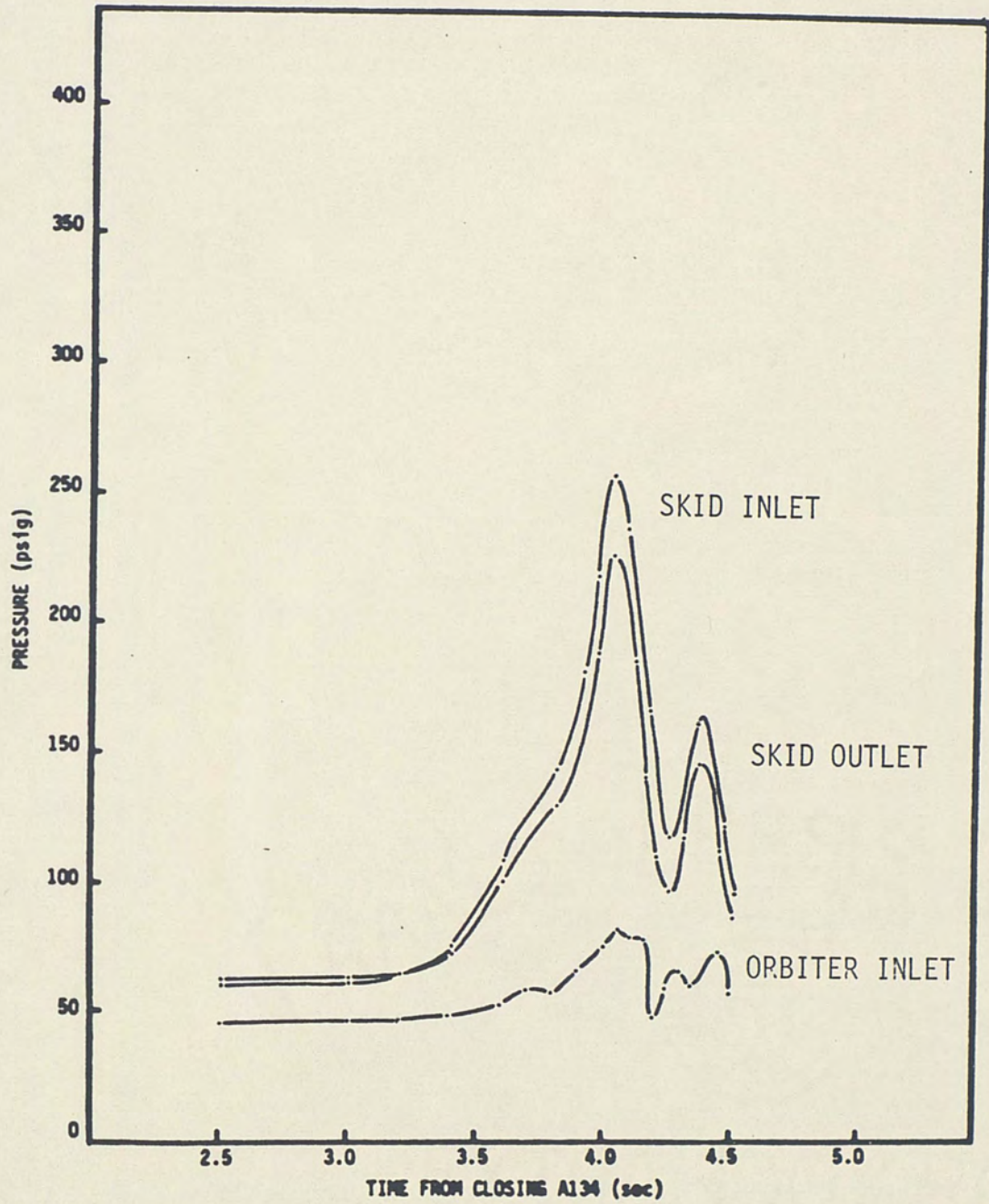


Fig. 35. Effect of system geometry (100 ft lengthening of pipeline between skid outlet and orbiter inlet). A lengthening of the pipeline between skid outlet and orbiter inlet by 100 ft increases the first pressure spike ($a = 2900$ ft/sec, no vapor chamber in the system).

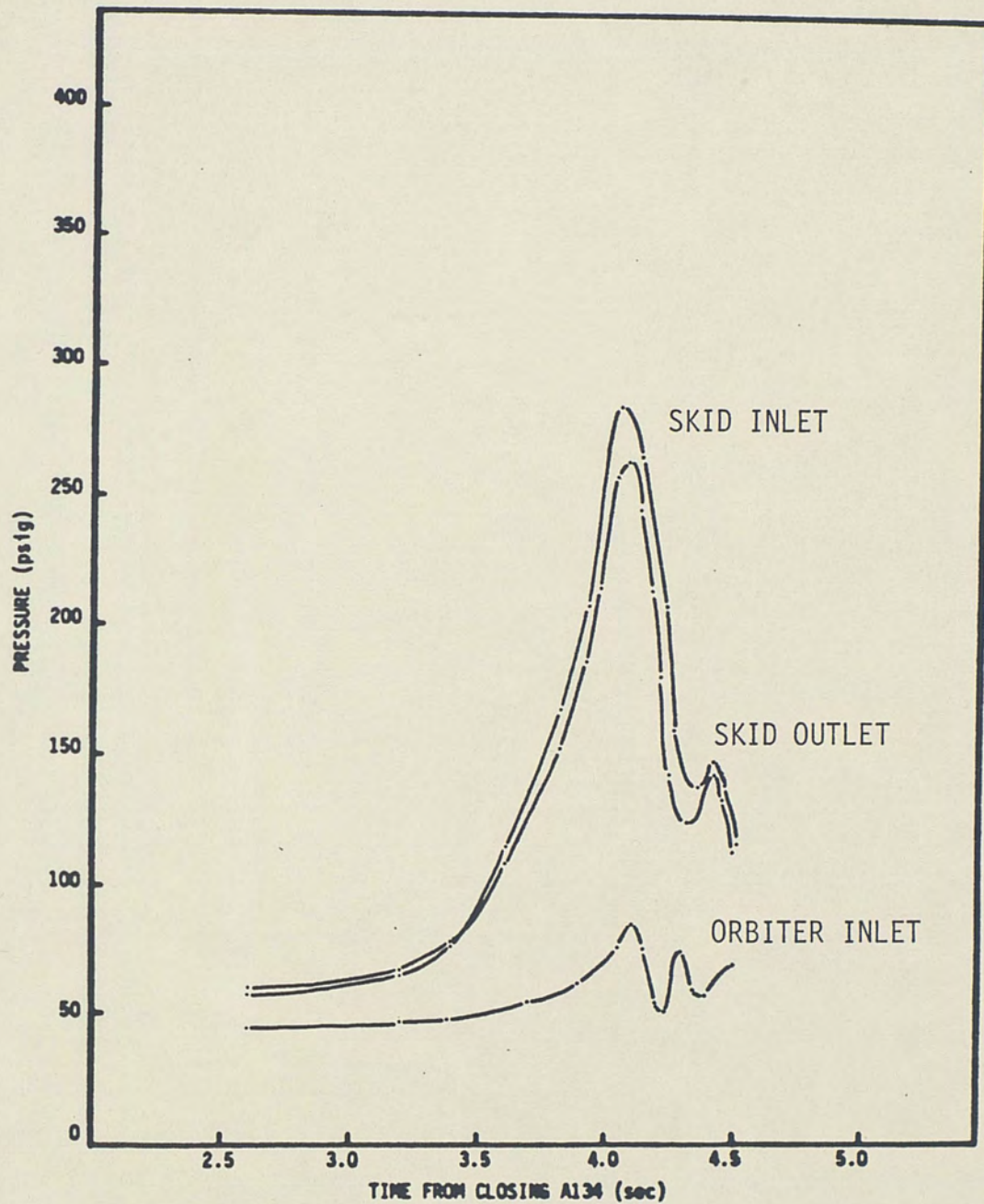


Fig. 36. Effect of system geometry (200 ft lengthening of pipeline between skid outlet and orbiter inlet). A lengthening of the pipeline between skid outlet and orbiter inlet by 200 ft increases the first pressure spike and reduces the secondary peaks. ($a = 2900$ ft/sec, no vapor chamber in the system).

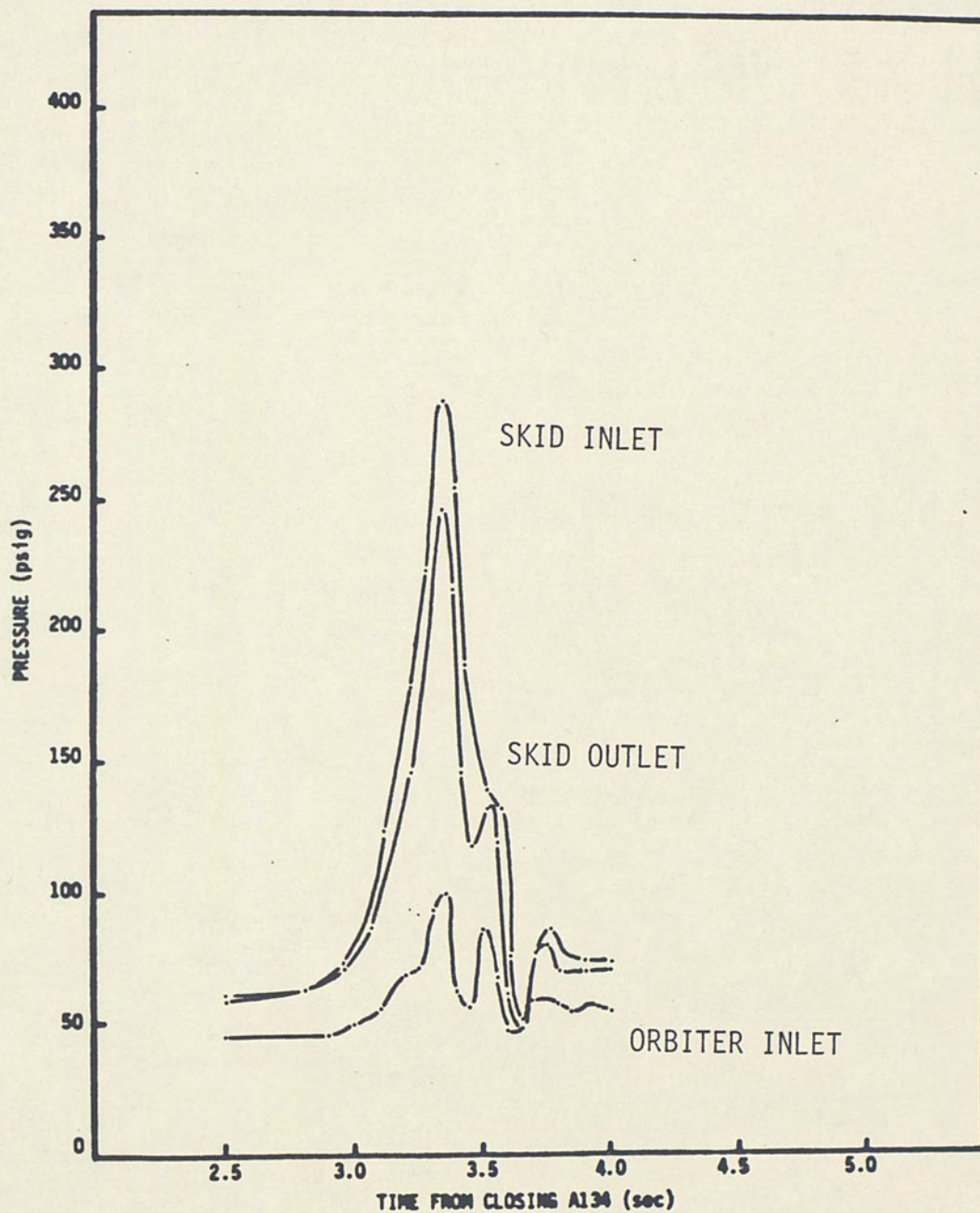


Fig. 37. Effect of valve closure time. A reduction by half of the valve A134 closure time increases the pressure spike and changes the peak occurrence time.

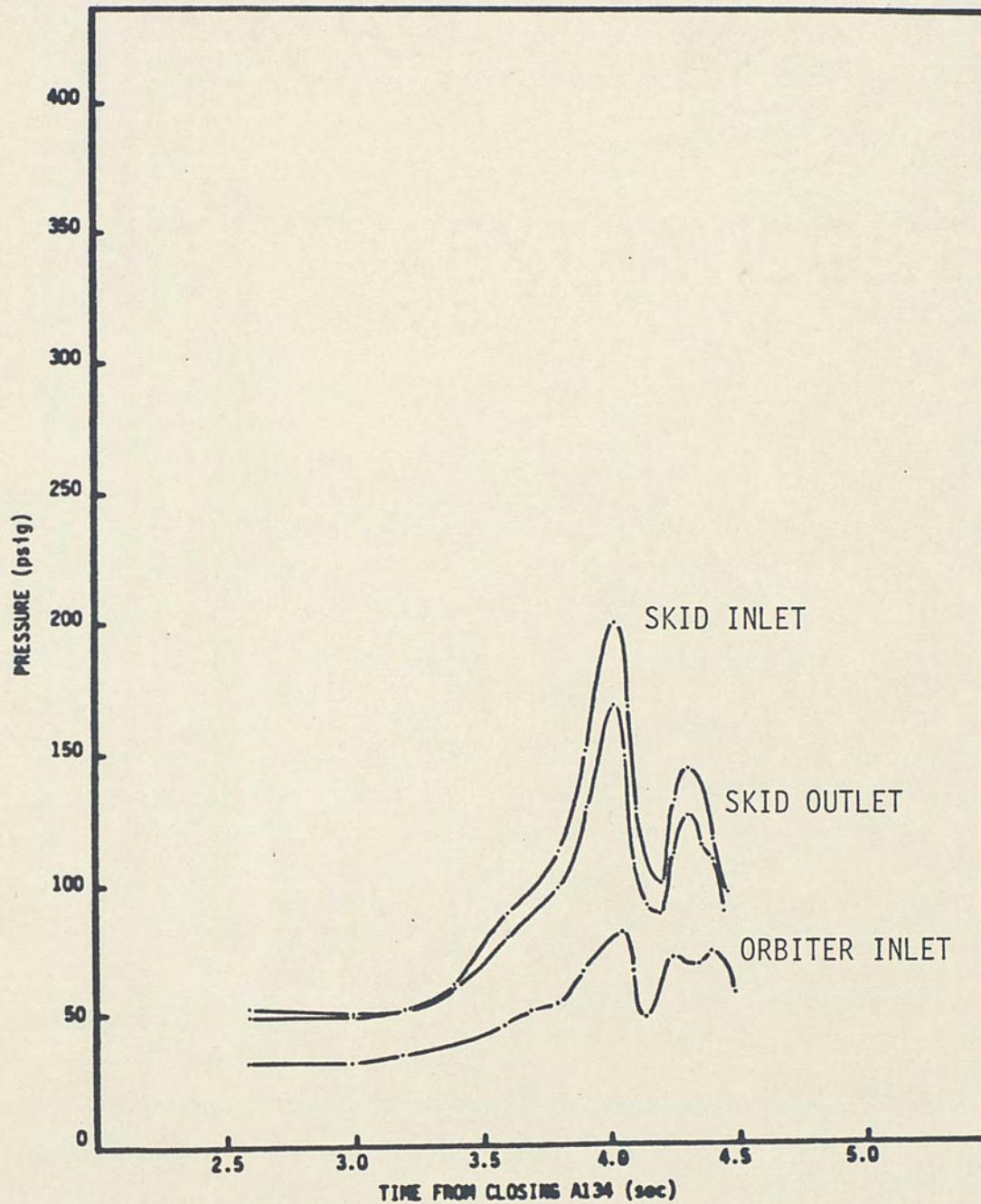


Fig. 38. Effect of valve constant. A reduction by a factor 3 of the PV10 C44 valve constant reduces the steady state pressures but has little influence on the pressure spikes ($a = 2900$ ft/sec, no vapor chamber in the system).

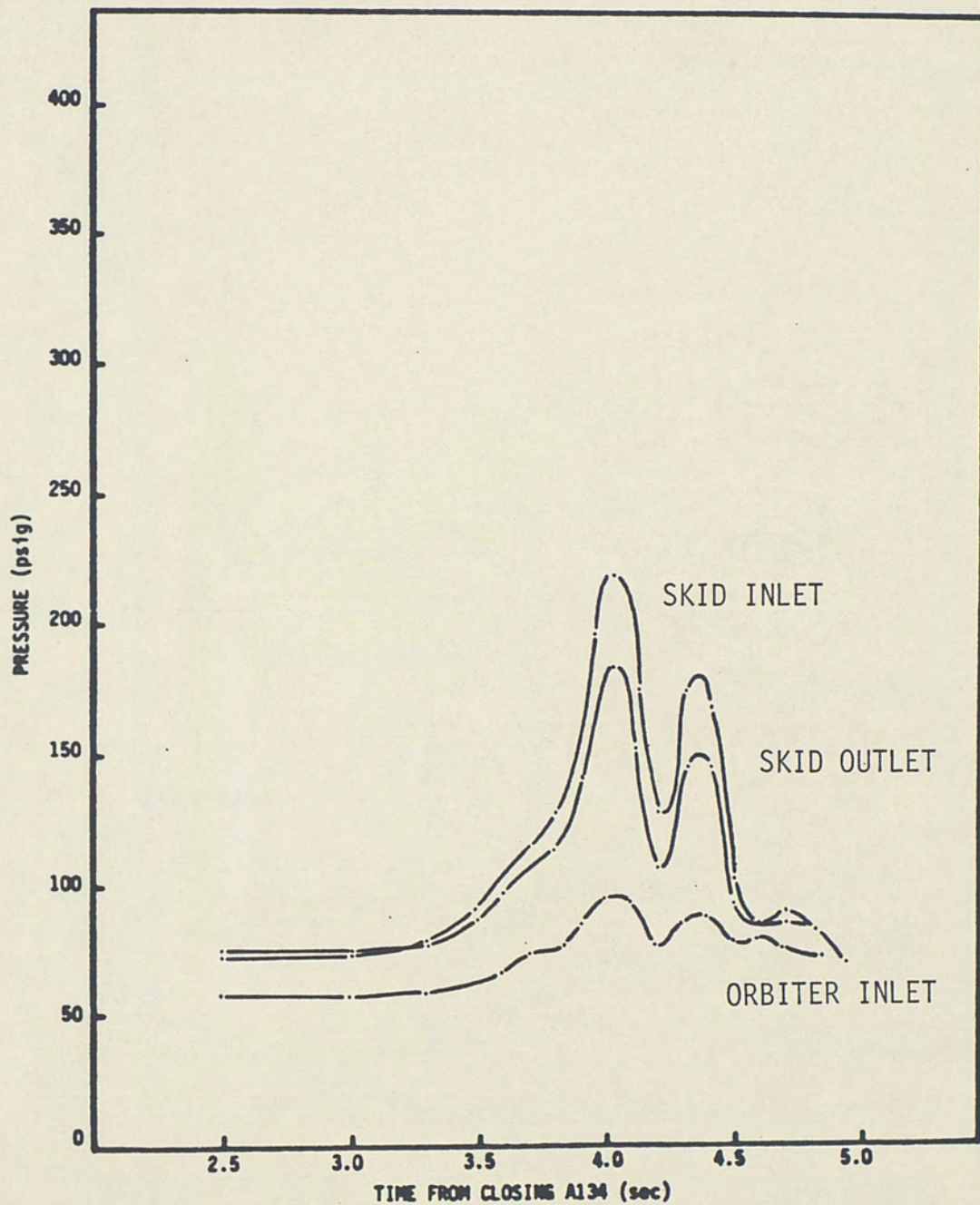


Fig. 39. Effect of piping system model. Data obtained with the first piping system model (27 pipes, 25 junctions, small reach length, requiring large computer time, more detail in appendix D). ($a = 3000$ ft/s, no vapor chamber in the system).

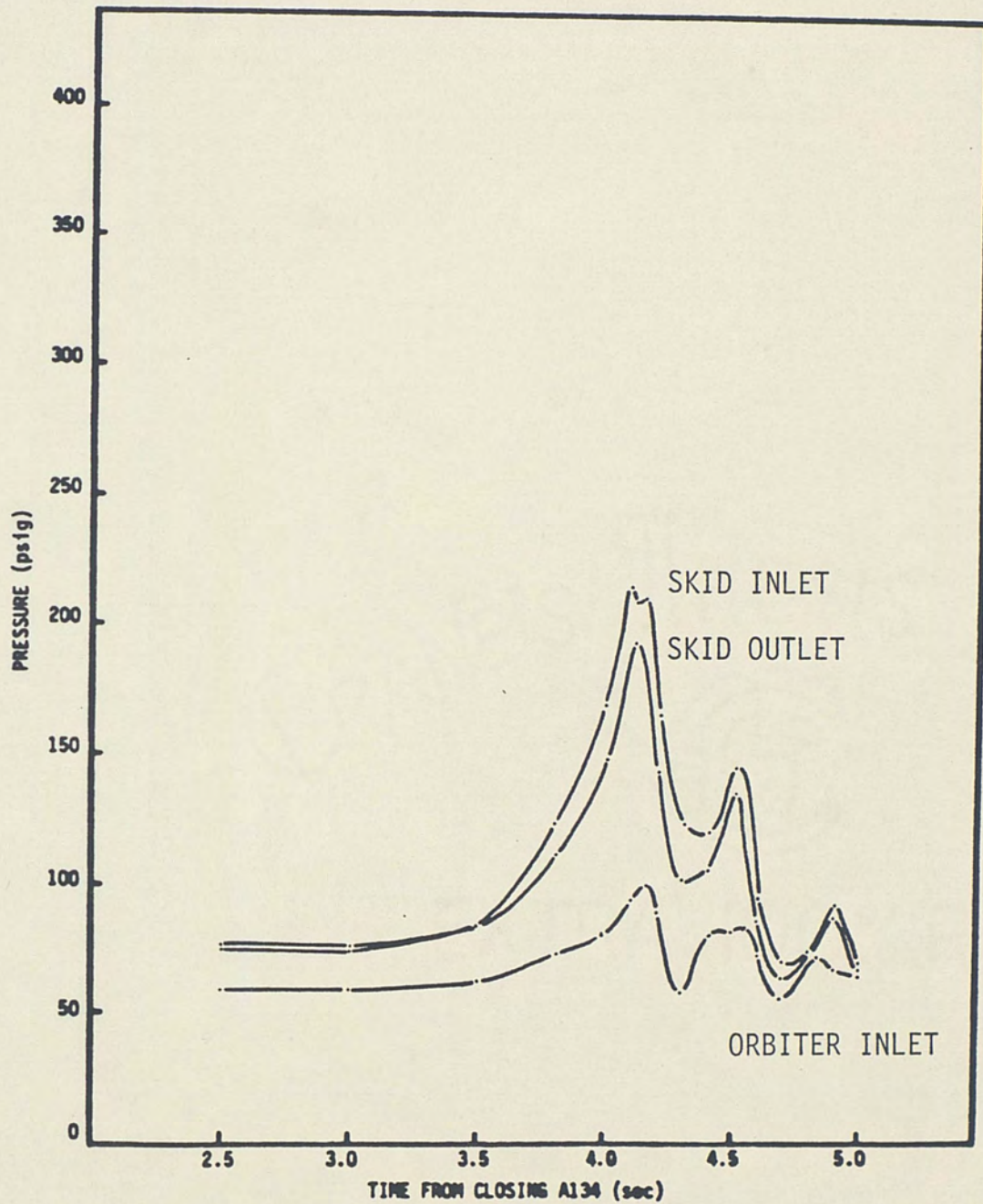


Fig. 40. Effect of lumped capacitance ($K = 300,000$ lb/ft²). The introduction of a lumped capacitance ($K = 300,000$ lb/ft²) at junction number 7 reduces the second peak.

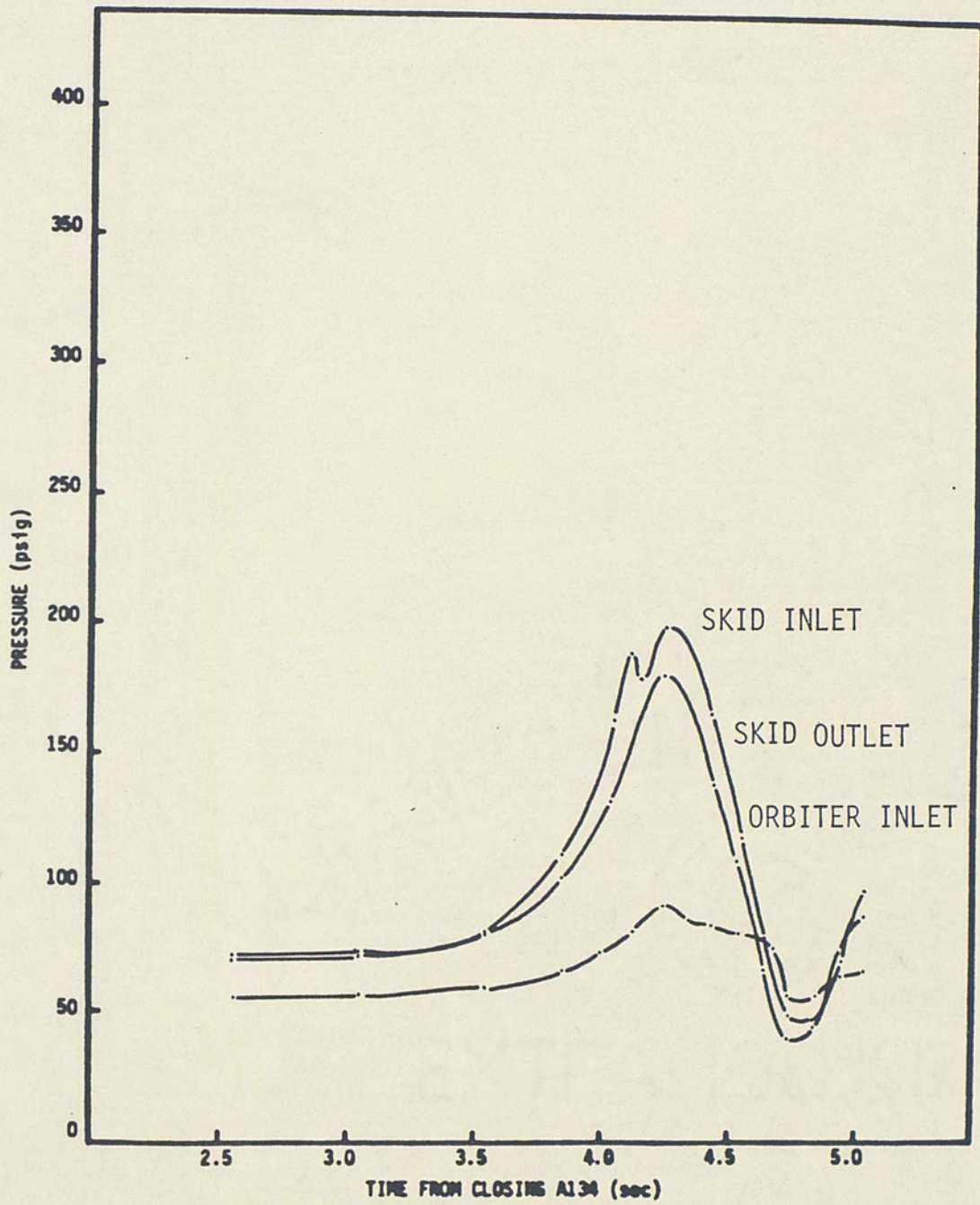


Fig. 41. Effect of lumped capacitance ($K = 60,000$ lb/ft²). Further reduction of the second peak by introduction of a lumped capacitance ($K = 60,000$ lb/ft²) at junction number 7.

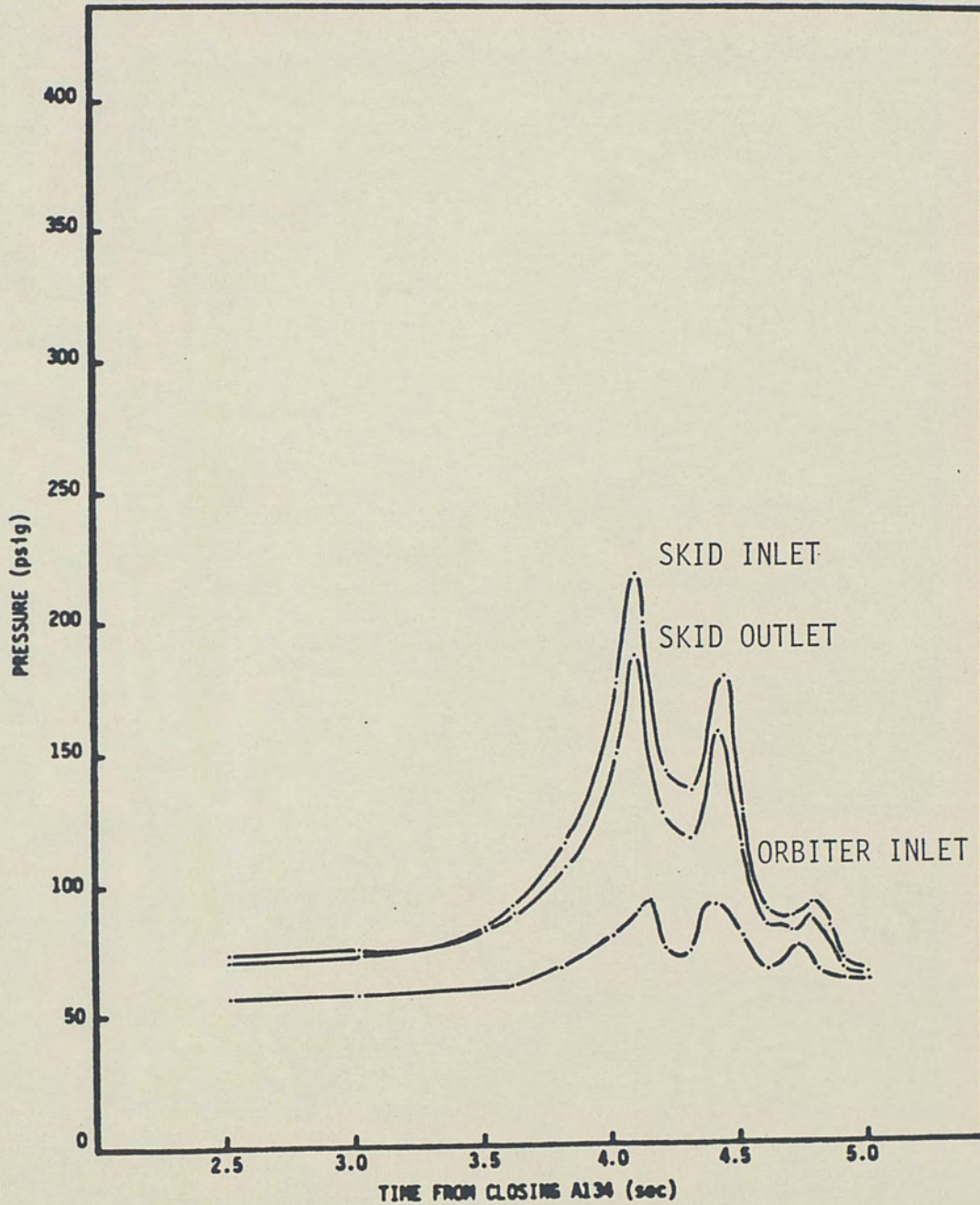


Fig. 42. Effect of lumped inertia. The introduction of a lumped inertia at junction 7 increases the skid inlet maximum and decreases the skid outlet maximum.

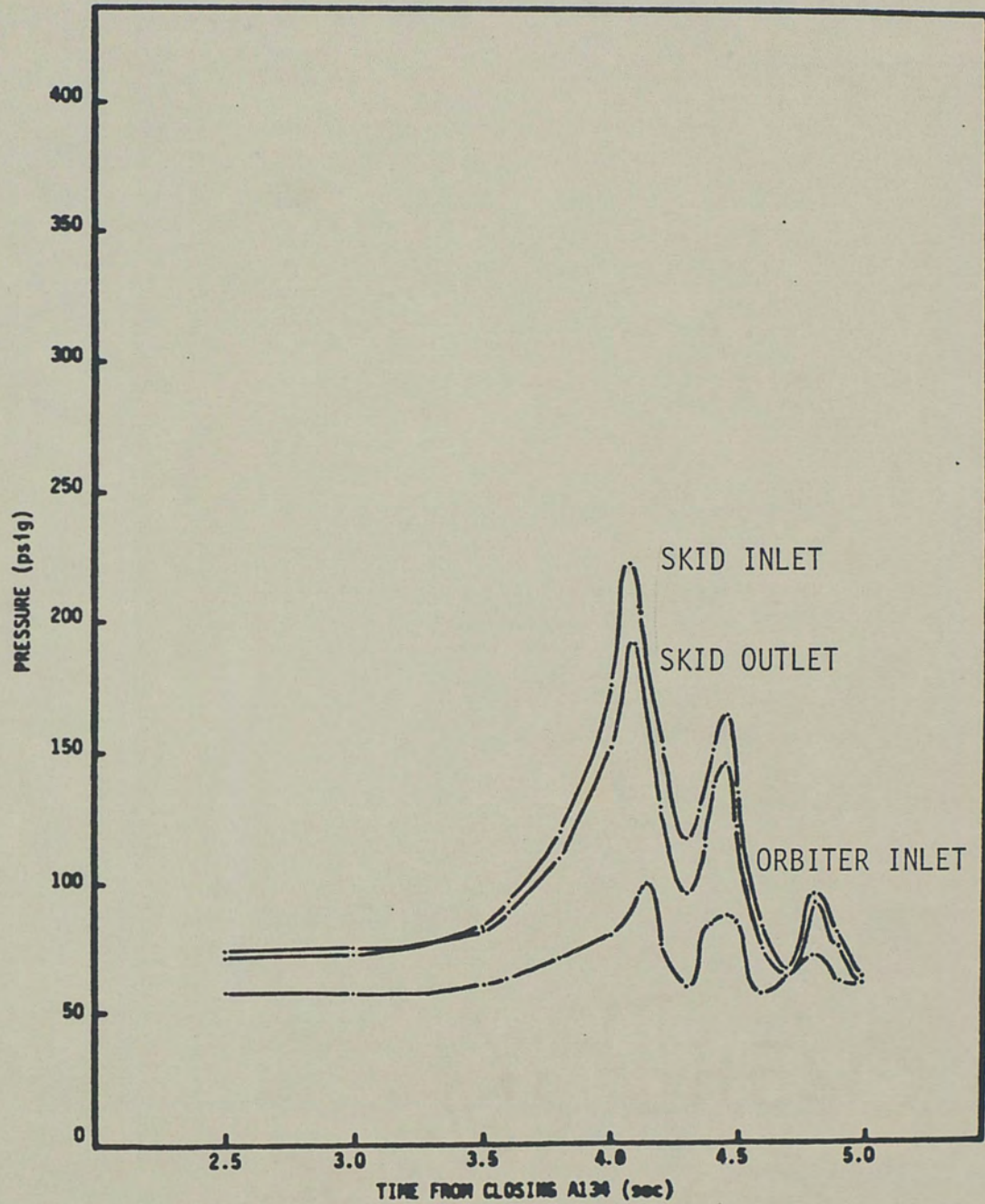


Fig. 43. Effect of a surge tank. A surge tank at junction 5 combines the effects of a lumped inertia and an air chamber.

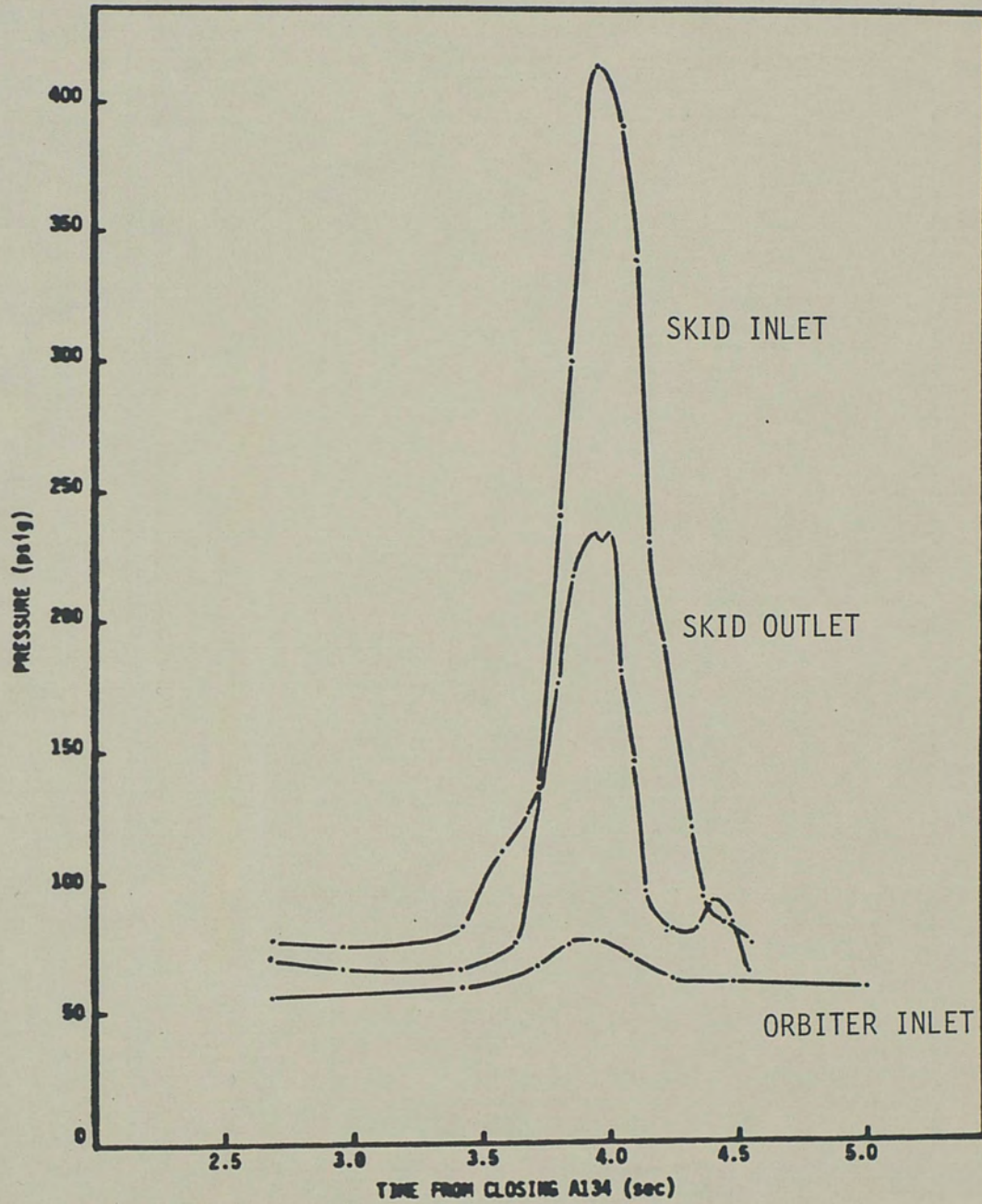


Fig. 44 . Measured pressure spikes. Measured pressure spikes without liquid column separation and vapor cavity collapse.

APPENDIX G

TWO-PHASE FLOW

Two-Phase-Flow Classical Approach

The pressure spike data with vapor cavities were obtained during a drain flow initiation on September 15, 1981. Before drain initiation, the storage tank was at 73% level, the E.T. was 90% level and the valves A134, A196, A86483 and A86462 were open. The valves A86460, A86461 and PV10 were closed leaving the transfer line section between A86461 and PV10 with O₂ vapor.

The drain was initiated by backfilling this void section by pressurizing the storage tank to 70 kPa gage, closing A134, A86462, opening A86460 to 100% open and running the pump at 2476 revolutions per minute. When the backfill flow was stabilized, PV10 was opened, A86483 closed, A86460 positioned to 15% the E.T. pressurized to 41 kPa gage, the pump turned off and the storage tank vented. Finally the main fill valve A86461 is opened.

Since the main fill valve A86461 was commanded to open 100 seconds after the replenish valve A86460 was positioned to 15% steady state flow conditions may be expected for most of the time. The liquid column started to separate downstream of the replenish valve.

Assuming steady state conditions, the vapor cavity length after a hundred seconds can be determined by calculating the velocities of the

downstream and the upstream columns. The difference of these two velocities multiplied by the time yields the cavity length.

This method can also give a first approximation of the time and magnitude of the first pressure spike. Assuming again that the vapor cavity is reabsorbed under steady state conditions once the main fill valve A86461 is opened, the upstream column velocity yields the time required to collapse the cavity and the magnitude of the pressure spike resulting from the difference in velocity of the upstream and downstream liquid columns.

Downstream Velocity

From Table 6 (Appendix E) the losses in the line at the ground side of the replenish valve are due to

- the friction in the pipe

$$\frac{\Delta H}{\frac{2}{q_D}} = \left(\frac{18649.77 - 6.08 - 15.17 - 37.83 - 62.80 - 230.76 - 15.13 - 287.66}{(3637)^2} \right) 0.0088$$

$$\frac{\Delta H}{\frac{2}{q_D}} = 11.97$$

- the valves

$$\frac{\Delta H}{\frac{2}{q_D}} = \left(\frac{1.54 + 0.84 + 8.50 + 0.96}{(3.637)^2} \right) + \frac{0.0503 (2585)}{(0.25)^4} \left(\frac{1}{258} + \frac{1}{17917} \right)$$

$$\frac{\Delta H}{\frac{2}{q_D}} = 131.77$$

NOTE: The value of the constant C_{44} is 258, corresponding to the two orifices 1.35" and 0.430" in parallel for a sonic velocity of 2585 ft/s.

The C_{44} value is 17917, corresponding to the valve A196.

$$\text{Finally } (\Delta H)_{\text{tot}} = 143.74 q_D^2$$

Applying Bernouilli's equation to this column and assuming that the vapor pressure is 4 ft gage yields

$$Z(8) + H(8) + \frac{V^2(8)}{2g} = Z(22) + H(22) + \frac{V^2(22)}{2g} + (\Delta H)_{\text{tot}}$$

$$\text{or } Z(8) + H(8) - Z(22) + H(22) = \left(\frac{4}{2g\pi} \left(\frac{1}{D^2(22)} - \frac{1}{D^2(8)} \right) + 143.74 \right) q_D^2$$

$$(85 + 4 - 53.2) = \left(\frac{4}{64.4\pi} \left(\frac{1}{(30)^2} - \frac{1}{(0.5)^2} \right) + 143.74 \right) q_D^2$$

$$q_D = 0.50 \text{ ft}^3/\text{s}$$

$$\text{so } V_D = 2.54 \text{ ft/s}$$

Upstream Velocity

The upstream velocity is determined by the replenish valve opened 15%.

$$\tau_R = 15\%$$

coefficient for the replenish valve.

$$\tau_M = \tau_R \frac{(C_V)_R}{(C_V)_M} \quad \text{equivalent coefficient for the main fill valve.}$$

Also holds across the valve

$$\Delta H = \frac{0.0503 a}{(C_{44})_M (\tau)_M^2 D^4} q_U^2 \quad (\text{see Appendix B})$$

$$\text{where } (C_{44})_M = 17917$$

$$\tau_M = \frac{0.15(46)}{2000} = 0.00345$$

$$\Delta H = HT(1) - Z(8) - H(8) = 272 - 85 - 4 \quad (\text{height of liquid column upstream})$$

$$\Delta H = 183 \text{ ft.}$$

$$\text{so } q_U = 0.137 \text{ ft}^3/\text{s}$$

$$V_U = 0.70 \text{ ft/s}$$

Cavity Length

The cavity length after one hundred seconds is

$$CAVL = (V_D - V_U) 100 = 184 \text{ ft.}$$

It can be observed that pipe 8 is nearly filled with only vapor after a period of 100 seconds.

Cavity Collapse

Assuming the 4.75" orifice square edged, $C \approx 0.65$ yielding $(\Delta H)_8 = 32.7 \text{ ft.}$ After the main fill valve is opened, the upstream column is accelerated while the downstream column still flows with the same velocity until both columns meet.

Assuming again that steady state conditions are reached and applying Bernouilli's equation to the column upstream of the middle of pipe 8 yields.

$$272 = Z(8) + H(8) + \frac{V^2(8)}{2g} + \Delta H$$

$$\text{where } \Delta H = (HT(1) - \frac{HT(8) + HT(q)}{2}) \frac{q^2}{(3.637)^2} = \frac{(246.7 - 196.4)}{(3.737)^2} q^2$$

$$\Delta H = 3.805 q^2$$

$$\text{so } 272 = 85 + 4 + \frac{V^2(8)}{2g} + 3.805 q^2$$

$$183 = \left(\frac{4}{64.4 \pi D^2(8)} + 3.805 \right) q^2$$

$$q = 6.864 \text{ ft}^3/\text{s}$$

$$V = 35.0 \text{ ft/s}$$

It will take at least

$$\frac{184}{35.0 - 2.54} = 5.7 \text{ sec}$$

to collapse the whole cavity. The expected pressure spike will be the order of

$$\left(\frac{35.0 - 2.54}{2} \right) \frac{a}{g} = 645 \text{ psi}$$

This pressure is an overestimated value.

Two-Phase Flow Transient Analysis

The column separation due to the positioning of the replenish valve at 15% was successfully modelled by the modified HYTRAN code.

As initial steady state conditions a zero velocity in each pipe has been chosen, followed by the opening of the valve A196 in the storage area, leaving the replenish valve 15% open. Again a 15% replenish valve coefficient corresponds to 0.00345 for the main fill valve (see first section of this Appendix). The pressure head in the E.T. tank 90% full + 41 kPa gage corresponds to an equivalent head of 272 feet (same as for the classical approach).

The same model as for the one one phase flow was used and only a few parameters in the input data had to be changed to simulate the flow with liquid column separation. The changed data are listed below:

DELT = 0.00245

TMAX = 117.,

HT = 13 * 272., 9 * 53.2,

VO = 40 * 0.,

NTAU = 7 * 0, 10, 5 * 0, 2 * 10,

TIME = 70 * 0., 105., 105.6, 105.9, 106.2, 106.5, 106.8, 107.1,
107.4, 107.7, 108., 60 * 0., 0.9, 0.76, 1.14, 1.52, 1.9,
2.28, 2.66, 3.04, 3.42, 3.8,

TAUV = 70 * 0., 0.00345, 0.02, 0.05, 0.12, 0.19, 0.29, 0.42,
0.53, 0.69, 1.0, 60 * 0., 0.0, 0.01, 0.05, 0.12, 0.19,
0.29, 0.42, 0.53, 0.69, 1.0,

The following comments can be made:

1. The timestep Δt has been chosen in such a manner as to satisfy the inequality

$$\Delta t \leq \frac{L}{a + V}$$

but as close as possible to the equal sign. Halving the timestep would first double the CPU time which is in the order of one and a half hours (since the real simulation time is $T_{MAX} = 117$ sec) and yield results far different from the actual ones as one run proved (neither the peaks timing, nor their amplitude were obtained with a halved timestep).

2. The opening time of valve A196 has been chosen arbitrarily 3 sec. The valve A134 remained closed during the whole analysis and the flow through the 0.43" orifice in the bypass loop could not be neglected any more since it represented about 10% of the drain flow (through valve A196). An equivalent C_V value equal to 60 (corresponding to $C_{44} = 258$ from first section in this Appendix) has been attributed to the valve A196.

Results

The program was run twice with only one change in the input data. The first run considered the orifice 4.75" at the orbiter inlet as a nozzle and the second as being rather sharp edged (with rounded edges). The difference resulted in the discharge coefficient, i.e., C_V coefficient. This change did not affect the cavity creation, only the cavity collapse, since the velocity of the upstream column filling back the cavity was different from one case to another. This had a double

effect on the pressure spikes, since it affected both the timing and the peak amplitude (see equation (1) in Chapter 1).

A comparison of the classical approach with the transient analysis reveals good agreement. Less than 5% difference is obtained for the velocities, the maximum cavity length and the first peak magnitude as show the output extracts Table 8, 9. In Table 8 the upstream velocity after 100 seconds is constant and equals 0.70 ft/s. This value is found in column "Velocity Upstream End" at pipe number 8 (Table 8). The downstream velocity of the fluid is found to be 2.43 ft/s. The cavity is located in pipe 8 and composed of three large bubbles as indicates the variable $NCAV(8) = 3$. The vapor cavity length after a hundred seconds is 169.16 ft (right column). Table 9 gives the pressures, velocities and cavity length 4 sec after the main fill valve opened completely. the cavity is collapsing and the upstream velocity reaches the constant value of 33.43 ft/s which is close to the hand calculated estimation (less than 5% difference). Although the downstream velocity should be identical to the one of Table 8 a slight increase is noticed. This letter error is due to limitations of the method used to model a flow with bubbles at the junctions. At the junction of two pipes boundary conditions are introduced and may not be compatible with the requirements of vapor cavity formation (pressure fixed at vapor pressure). For this reason no cavity formation has been allowed in the last sections at the ends of the pipes. However this approximation does not affect significantly the magnitude and timing of the pressure spikes.

TABLE 8

OUTPUT SAMPLE WITH VAPOR CAVITY FORMATION

SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.99964E+02 SEC						
PIPE NO.	PRESSURE HEAD UP STREAM END PSI	PRESSURE HEAD DN STREAM END PSI	VELOCITY UP STREAM END FT/SEC	VELOCITY DN STREAM END FT/SEC	VAPOR CAVITY LENGTH FT	
1	0.24559E+02	0.72636E+02	0.87685E-01	0.87437E-01	0.00000E+00	
2	0.72637E+02	0.73570E+02	0.39406E+00	0.39404E+00	0.00000E+00	
3	0.73569E+02	0.75441E+02	0.39404E+00	0.39402E+00	0.00000E+00	
4	0.75420E+02	0.88062E+02	0.39402E+00	0.39472E+00	0.00000E+00	
5	0.87765E+02	0.90772E+02	0.39401E+00	0.39404E+00	0.00000E+00	
6	0.91090E+02	0.91082E+02	0.39404E+00	0.39368E+00	0.00000E+00	
7	0.91082E+02	0.92582E+02	0.70057E+00	0.70097E+00	0.00000E+00	
8	0.99811E+00	0.99028E+00	0.70097E+00	0.23817E+01	0.16916E+03	
NCAV(8)= 3						
9	0.99028E+00	0.20537E+02	0.23817E+01	0.24346E+01	0.00000E+00	
10	0.20537E+02	0.35443E+02	0.24346E+01	0.24344E+01	0.00000E+00	
11	0.35457E+02	0.36153E+02	0.24344E+01	0.24453E+01	0.00000E+00	
12	0.36116E+02	0.34468E+02	0.24453E+01	0.24409E+01	0.00000E+00	
13	0.34468E+02	0.34471E+02	0.37631E-02	0.00000E+00	0.00000E+00	
14	0.18096E+02	0.18174E+02	0.00000E+00	-0.16412E-02	0.00000E+00	
15	0.34468E+02	0.34012E+02	0.97484E+01	0.97461E+01	0.00000E+00	
16	0.33699E+02	0.33322E+02	0.97461E+01	0.97407E+01	0.00000E+00	
17	0.18705E+02	0.18174E+02	0.97407E+01	0.97396E+01	0.00000E+00	
18	0.18174E+02	0.19651E+02	0.24333E+01	0.24307E+01	0.00000E+00	
19	0.19575E+02	0.19890E+02	0.24307E+01	0.24256E+01	0.00000E+00	
20	0.19890E+02	0.19926E+02	0.60639E+00	0.60388E+00	0.00000E+00	
21	0.19917E+02	0.17619E+02	0.60388E+00	0.59587E+00	0.00000E+00	
22	0.17619E+02	0.99028E+00	0.66209E-03	0.15981E-01	0.00000E+00	
MAXIMUM HEAD (PSI)						
SKID INLET :	0.10083E+01	AT T=	0.97708E+02	SEC		
SKID OUTLET :	0.90792E+02	AT T=	0.90168E+02	SEC		
ORBITER INLET :	0.75453E+02	AT T=	0.90574E+02	SEC		
DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED						
VOLTKT, VOLTKG, VOLTKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY						
0.24585E+05	0.23437E+04	0.22241E+05	0.27200E+03	0.22240E+03	0.10300E+03	0.60588E+01

TABLE 9
OUTPUT SAMPLE WITH VAPOR CAVITY COLLAPSE

SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.11198E+03 SEC									
PIPE NO.	PRESSURE HEAD UP STREAM END PSI		PRESSURE HEAD DN STREAM END PSI		VELOCITY UP STREAM END FT/SEC		VELOCITY DN STREAM END FT/SEC		VAPOR CAVITY LENGTH FT
1	0.24525E+02		0.72509E+02		0.41718E+01		0.41697E+01		0.00000E+00
2	0.72510E+02		0.73253E+02		0.18792E+02		0.18792E+02		0.00000E+00
3	0.72451E+02		0.73941E+02		0.18792E+02		0.18790E+02		0.00000E+00
4	0.25469E+02		0.37172E+02		0.18790E+02		0.18776E+02		0.00000E+00
5	0.36875E+02		0.36564E+02		0.18790E+02		0.18786E+02		0.00000E+00
6	0.33806E+02		0.33540E+02		0.18786E+02		0.18786E+02		0.00000E+00
7	0.33540E+02		0.31049E+02		0.33431E+02		0.33426E+02		0.00000E+00
8	0.28542E+02		0.22166E+02		0.33426E+02		0.36806E+01		0.28721E+02
NCAV(8)= 1									
9	0.22166E+02		0.41533E+02		0.36806E+01		0.36791E+01		0.00000E+00
10	0.41533E+02		0.56981E+02		0.36791E+01		0.36776E+01		0.00000E+00
11	0.56996E+02		0.55802E+02		0.36776E+01		0.36758E+01		0.00000E+00
12	0.55723E+02		0.54069E+02		0.36758E+01		0.36757E+01		0.00000E+00
13	0.54069E+02		0.54050E+02		-0.53048E-03		0.00000E+00		0.00000E+00
14	0.19028E+02		0.19023E+02		0.00000E+00		0.30810E-03		0.00000E+00
15	0.54069E+02		0.53617E+02		0.14705E+02		0.14705E+02		0.00000E+00
16	0.53201E+02		0.52772E+02		0.14705E+02		0.14705E+02		0.00000E+00
17	0.19456E+02		0.19023E+02		0.14705E+02		0.14707E+02		0.00000E+00
18	0.19023E+02		0.20481E+02		0.36770E+01		0.36770E+01		0.00000E+00
19	0.20316E+02		0.20335E+02		0.36770E+01		0.36773E+01		0.00000E+00
20	0.20335E+02		0.20332E+02		0.91933E+00		0.91895E+00		0.00000E+00
21	0.20308E+02		0.17621E+02		0.91895E+00		0.91929E+00		0.00000E+00
22	0.17621E+02		0.99028E+00		0.10214E-02		0.16362E-01		0.00000E+00
MAXIMUM HEAD (PSI)									
SKID INLET :	0.28542E+02	AT T=	0.11198E+03	SEC					
SKID OUTLET :	0.36564E+02	AT T=	0.11198E+03	SEC					
ORBITER INLET :	0.25511E+02	AT T=	0.11193E+03	SEC					
DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED									
VOLTKT, VOLTKG, VOLTKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY									
0.24585E+05	0.23779E+04	0.22207E+05	0.27193E+03	0.22240E+03	0.10300E+03	0.60588E+01			

APPENDIX H

COMPUTER PROGRAM

In this Appendix a listing of the computer program HYTRAN (HYTRAN.FOR; 60) and a sample input and output data for single phase flow (HYTRAN.DAT; 10 and HYTRAN.RPT; 55 respectively) can be found.


```

VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:

```

```

U  U  CCCC  FFFF
U  U  C    F
U  U  C    F
U  U  C  FFFF
U  U  C    F
U  U  C    F
UUUUU  CCCC  F

```

```

HH      HH  YY      YY  TTTTTTTTTT  RRRRRRRR      AAAAAA  NN      NN
HH      HH  YY      YY  TTTTTTTTTT  RRRRRRRR      AAAAAA  NN      NN
HH      HH  YY      YY      TT      RR      RR  AA      AA  NN      NN
HH      HH  YY      YY      TT      RR      RR  AA      AA  NN      NN
HH      HH      YY  YY      TT      RR      RR  AA      AA  NNNN      NN
HH      HH      YY  YY      TT      RR      RR  AA      AA  NNNN      NN
HHHHHHHHHH      YY      TT      RRRRRRRR      AA      AA  NN  NN  NN
HHHHHHHHHH      YY      TT      RRRRRRRR      AA      AA  NN  NN  NN
HH      HH      YY      TT      RR  RR      AAAAAAAAAA  NN      NNNN
HH      HH      YY      TT      RR  RR      AAAAAAAAAA  NN      NNNN
HH      HH      YY      TT      RR      RR  AA      AA  NN      NN      ....
HH      HH      YY      TT      RR      RR  AA      AA  NN      NN      ....
HH      HH      YY      TT      RR      RR  AA      AA  NN      NN      ....
HH      HH      YY      TT      RR      RR  AA      AA  NN      NN      ....

```

```

FFFFFFFFFF  000000  RRRRRRRR      1111  666666  000000
FFFFFFFFFF  000000  RRRRRRRR      1111  666666  000000
FF          00      00  RR      RR      1111  66      00      00
FF          00      00  RR      RR      1111  66      00      00
FF          00      00  RR      RR      1111  66      00      0000
FF          00      00  RR      RR      1111  66      00      0000
FFFFFFFFFF  00      00  RRRRRRRR      1111  66666666  00  00  00
FFFFFFFFFF  00      00  RRRRRRRR      1111  66666666  00  00  00
FF          00      00  RR  RR      1111  66      66  0000  00
FF          00      00  RR  RR      1111  66      66  0000  00
FF          00      00  RR      RR      1111  66      66  00      00
FF          00      00  RR      RR      1111  66      66  00      00
FF          00      00  RR      RR      1111  66      66  00      00
FF          000000  RR      RR      11  666666  000000
FF          000000  RR      RR      11  666666  000000

```

```

U  U  CCCC  FFFF
U  U  C    F
U  U  C    F
U  U  C  FFFF
U  U  C    F
U  U  C    F
UUUUU  CCCC  F

```

```

VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:26  LPA0:  6-JUL-1983 16:26  DISK$VAXVMSRL3:

```



```
C
C
C
C
** MAIN PROGRAM FOR HYTRAN PROGRAM **

COMMON /IN1/ NP(30), NSORCE(30), NSINK(30), NSTANK(30), HT(30),
1 C1P(30), C2P(30), C3P(30), VOL(30), VOLMIN(30), GAMMA(30), KK(30),
2 CD(30), C4P(30), G(30), GP(30), FLI(30), DLI(30), XLI(30), VOLMAX(30)
COMMON /INA/ D(40), XL(40), VO(40), A(40), ALPHA(40), F(40), FF(40)
COMMON /IN2/ C44(30), CV(30), IC(30, 5), JJ(30, 5), NTAU(30), TIME(10, 30),
1 TAUV(10, 30), TMD(10), TAUD(10)
COMMON /IN3/ NJCT, NPIPE, DELT, T, TMAX, ITPRNT, ISTOP, LPRT, LPLT,
1 ITPLT, LTAPE, ITTPE, NJPLT, JPLT(30), TIME2, ITPR2, TIME3, ITPR3
2 , TIME4, ITPR4
COMMON /BK1/ XN(40), DELX(40), THETA(40), N(40), C1(40), C3(40), C2(40),
1 H1M(40), HNM(40), T1(40), TN(40), HT1(30), DHEAD(30), SHEAD(30), ELEV(30)
COMMON /BK2/ V(40, 200), H(40, 200), VS(40, 200), HS(40, 200),
1 VR(40, 200), VD(40, 200),
1 HR(40, 200), VP(40, 200), HP(40, 200), XIC(30, 5), C(30, 5)
COMMON /BK3/ Q, PI, RHO, VARPR, TITLE(20), ICTR, KNTAPE, IRUN
1 , ISTART, IDATPE
COMMON /BUBBL/ VDP(40, 200), XCAV(40, 200), CAVL(40), NCAV(40), HST(40)
COMMON /TANK/ ITANK1, RADTK1, XHIGH1, XHIGH2, XDIST, VOLTKT, VOLTKG,
1 VOLTKL, VFLOIN, TKLENG
OPEN(5, FILE='HYTRAN.DAT', STATUS='OLD')
OPEN(6, FILE='HYTRAN.RPT', STATUS='NEW')

C
1 CALL INPUT
CALL INIT
GO TO (2, 10), IRUN

C
2 CONTINUE
CALL TMSTEP
CALL STATE
CALL BOUDRY
CALL PHASE
IF (ITANK1 .NE. 0) CALL TMFUNC
CALL OUTPUT
IF (T .LT. TMAX) GO TO 2
IF (LTAPE .EQ. 0) GO TO 4
WRITE (6, 5) KNTAPE
FORMAT (/1X, 'KNTAPE=', I10)
5 IF (LPLT .EQ. 0) GO TO 3
CALL PLOTT
CONTINUE
3 IF (ISTOP .EQ. 0) GO TO 1
GO TO 999

C
10 CALL PLOTT
IF (ISTOP .EQ. 0) GO TO 1

C
999 CLOSE(5, STATUS='KEEP')
CLOSE(6, STATUS='KEEP')
STOP
END
SUBROUTINE INPUT

C
C
C
** ROUTINE TO READ IN DATA **

COMMON /IN1/ NP(30), NSORCE(30), NSINK(30), NSTANK(30), HT(30),
```



```

1 C1P(30), C2P(30), C3P(30), VOL(30), VOLMIN(30), GAMMA(30), KK(30),

2 CD(30), C4P(30), G(30), GP(30), FLI(30), DLI(30), XLI(30), VOLMAX(30)
COMMON /INA/ D(40), XL(40), VO(40), A(40), ALPHA(40), F(40), FF(40)
COMMON /IN2/C44(30), CV(30), IC(30,5), JJ(30,5), NTAU(30), TIME(10,30),
1 TAU(10,30), TMD(10), TAUD(10)
COMMON /IN3/ NJCT, NPIPE, DELT, T, TMAX, ITPRNT, ISTOP, LPRT, LPLT,
1 ITPLT, LTAPE, ITTPE, NJPLT, JPLT(30), TIME2, ITPR2, TIME3, ITPR3
2 , TIME4, ITPR4
COMMON /BK1/ XN(40), DELX(40), THETA(40), N(40), C1(40), C3(40), C2(40),
1H1M(40), HNM(40), T1(40), TN(40), HT1(30), DHEAD(30), SHEAD(30), ELEV(30)
COMMON /BK2/ V(40,200), H(40,200), VS(40,200), HS(40,200),
1VR(40,200), VD(40,200),
1 HR(40,200), VP(40,200), HP(40,200), XIC(30,5), C(30,5)
COMMON /BK3/ G, PI, RHO, VARPR, TITLE(20), ITCTR, KNTAPE, IRUN
1 , ISTART, IDATPE
COMMON /BUBBL/ VDP(40,200), XCAV(40,200), CAVL(40), NCAV(40), HST(40)
COMMON /TANK/ ITANK1, RADTK1, XHIGH1, XHIGH2, XDIST, VOLTKT, VOLTKG,
1 VOLTKL, VFLOIN, TKLENG

C      NAMELIST/DIN/NJCT, NPIPE, DELT, TMAX, NP, NSORCE, NSINK, NSTANK, HT, C1P,
1 C2P, C3P, C4P, VOL, VOLMIN, VOLMAX, GAMMA, CD, XLI, DLI, FLI, KK, D, XL, VO, A,
2 ALPHA, JJ, IC, CV, ELEV, N, F, NTAU, TIME, TAU

C
C      PUT PIPE ANGLES IN AS + FOR UP AND - FOR DOWN... COMPUTER WILL CHAN
C      READ (5,220) TITLE
220  FORMAT (20A4)
      WRITE (6,3) TITLE
3    FORMAT (1H1,50X, 'HYTRAN INPUT DATA'//40X,20A4,/)
      READ(5,DIN)
      WRITE (6,DIN)

C
      READ (5,1) ISTOP, RHO, VARPR, IRUN, ISTART, IDATPE, ITANK1
1    FORMAT (I10,2F10.2,4I10)
      WRITE (6,2) ISTOP, RHO, VARPR, IRUN, ISTART, IDATPE, ITANK1
2    FORMAT (//,2X, 'ISTOP', 5X, 'RHO, LB/FT**3',
1 8X, 'VARPR, FT', 8X, 'IRUN', 4X, 'ISTART', 4X, 'IDATPE', 4X, 'ITANK1'//
2 4X, I1, 4X, E15.5, 5X, E15.5, 5X, I1, 8X, I1, 6X, I5, 8X, I1)

C
      IF (ITANK1 .EQ. 0) GO TO 8

C
C      ITANK1=1 FOR SPHERICAL TANK, =2 FOR VERTICAL CYLINDRICAL TANK,
C      =3 FOR HORIZONTAL CYLINDRICAL TANK
C
      READ (5,9) RADTK1, XHIGH1, XHIGH2, TKLENG, VFLOIN
9    FORMAT (5F10.3)
      WRITE (6,7) RADTK1, XHIGH1, XHIGH2, TKLENG, VFLOIN
7    FORMAT (/6X, 'RADTK1, FT', 5X, 'XHIGH1, FT', 6X, 'XHIGH2, FT', 6X,
1 'TKLENG, FT', 6X, 'VFLOIN, FT**3/S'/4E15.5, E20.5)
8    CONTINUE

C
      READ (5,240) LPRT, ITPRNT, LPLT, ITPLT, LTAPE, ITTPE, TIME2, ITPR2, TIME3,
1 ITPR3, TIME4, ITPR4
240  FORMAT (6I5, F10.2, I5, F10.2, I5, F10.2, I5)
      WRITE (6,360) LPRT, ITPRNT, LPLT, ITPLT, LTAPE, ITTPE, TIME2, ITPR2,
1 TIME3, ITPR3, TIME4, ITPR4
360  FORMAT (/1X, 'OUTPUT PARAMETERS--LPRT, ITPRNT, LPLT, ITPLT, LTAPE, ITTPE
1 , TIME2, ITPR2, TIME3, ITPR3, TIME4, ITPR4'/1X, 6I5, F14.2, I5, F14.2, I5,
2 F14.2, I5)
      IF (LPLT .EQ. 0) GO TO 100
      READ (5,230) NJPLT
230  FORMAT (16I5)

```



```

WRITE (6,380) NJPLT

380  FORMAT (1X, 'NJPLT=', I5)
      READ (5,230) (JPLT(I), I=1, NJPLT)
      WRITE (6,390) (JPLT(I), I=1, NJPLT)
390  FORMAT (/1X, 'PLOT PARAMETERS--JPLT(I), I=1,2,...'/1X, 16I5)
100  CONTINUE
      RETURN
      END
      SUBROUTINE INIT
C
C      ** ROUTINE TO INITIALIZE TRANSIENT PROBLEM **
C
      COMMON /IN1/ NP(30), NSORCE(30), NSINK(30), NSTANK(30), HT(30),
1  C1P(30), C2P(30), C3P(30), VOL(30), VOLMIN(30), GAMMA(30), KK(30),
2  CO(30), C4P(30), Q(30), GP(30), FLI(30), DLI(30), XLI(30), VOLMAX(30)
      COMMON /INA/ D(40), XL(40), VO(40), A(40), ALPHA(40), F(40), FF(40)
      COMMON /IN2/C44(30), CV(30), IC(30,5), JJ(30,5), NTAU(30), TIME(10,30),
1  TAU(10,30), TMD(10), TAU(10)
      COMMON /IN3/ NJCT, NPIPE, DELT, T, TMAX, ITPRNT, ISTOP, LPRT, LPLT,
1  ITPLT, LTAPE, ITTPE, NJPLT, JPLT(30), TIME2, ITPR2, TIME3, ITPR3
2  , TIME4, ITPR4
      COMMON /BK1/ XN(40), DELX(40), THETA(40), N(40), C1(40), C3(40), C2(40),
1H1M(40), HNM(40), T1(40), TN(40), HT1(30), DHEAD(30), SHEAD(30), ELEV(30)
      COMMON /BK2/ V(40,200), H(40,200), VS(40,200), HS(40,200),
1VR(40,200), VD(40,200),
1  HR(40,200), VP(40,200), HP(40,200), XIC(30,5), C(30,5)
      COMMON /BK3/ G, PI, RHO, VARPR, TITLE(20), ITCTR, KNTAPE, IRUN
1  , ISTART, IDATPE
      COMMON /BUBBL/ VDP(40,200), XCAV(40,200), CAVL(40), NCAV(40), HST(40)
      COMMON /TANK/ ITANK1, RADTK1, XHIGH1, XHIGH2, XDIST, VOLTKT, VOLTKG,
1  VOLTKL, VFLOIN, TKLENG
C
      Q=32.2
      ITCTR=0
      KNTAPE=0
      T=0.
      PI=3.14159
C
      IF (NJCT .NE. 0) GO TO 3
51  WRITE (6,4)
4  FORMAT (1X, 'SOLUTION TERMINATED DUE TO NJCT=0')
      STOP
3  CONTINUE
      DO114J=1, NPIPE
114  ALPHA(J)=-ALPHA(J)*(3.14159/180.)
      DO2L=1, NJCT
      NL=NP(L)
      DO2M=1, NL
      IF (IC(L,M).EQ.0) GO TO 51
      J=JJ(L,M)
      HST(L)=HT(L)
      IF (NSINK(L).EQ.0) GO TO 121
      IF (M.GT.1) GO TO 116
      DUP=D(J)
      AUP=A(J)
      IF ((NSINK(L).EQ.2).OR.(NSINK(L).EQ.4).OR.
1  (NSINK(L).EQ.7)) GO TO 120
      GO TO 121
116  IF (M.GT.2) GO TO 117
      DDN=D(J)
      ADN=A(J)

```


GO TO 119

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117 WRITE(6,118) L
118 FORMAT(1X,'SOLUTION TERMINATED DUE TO BAD DATA
1 AT VALVE ',I2)
STOP
119 IF(AUP.NE.ADN) GO TO 117
IF(DUP.NE.DDN) GO TO 117
120 C44(L)=((1.083 E-7)*AUP*CV(L)**2)/(DUP**4)
121 IF(IC(L,M).GT.0)GOTO2
C2(J)=G/A(J)
IF (N(J) .EQ. 0) GO TO 51
XN(J)=N(J)
DELX(J)=XL(J)/XN(J)
NN=N(J)+1
IF(NSTANK(L).EQ.2) Q(L)=V0(J)*(PI/4.)*D(J)**2
D053I=1,NN
V(J,I)=V0(J)
VD(J,I)=V0(J)
X=I-1
H(J,I)=HT(L)-X*DELX(J)*((F(J)*V(J,I)**2)/(2.*D(J)*G))
VP(J,I)=V(J,I)
ELJI=ELEV(L)-X*DELX(J)*SIN(ALPHA(J))
53 HP(J,I)=H(J,I)-ELJI
I=1
H1M(J)=HP(J,I)
HNM(J)=HP(J,NN)
T1(J)=0.
TN(J)=0.
2 CONTINUE
C
IF (ISTART .EQ. 0) GO TO 5
READ (ISTART) IDUMP
DO 6 I=1, IDATPE
READ (ISTART) T, (HT(L),L=1,NJCT)
DO 7 J=1,NPIPE
NN=N(J)+1
7 READ (ISTART) (HP(J,M),VP(J,M),M=1,NN)
6 CONTINUE
5 CONTINUE
C
FOR TANK AT JUNCTION 1
IF (ITANK1 .EQ. 0) GO TO 1
XDIST=XHIGH1
IF (ITANK1 .NE. 1) GO TO 9
VOLTKT=4.*PI*RADTK1**3/3.
VOLTKG=PI*XHIGH1**2*(RADTK1-XHIGH1/3.)
GO TO 10
9 IF (ITANK1 .NE. 2) GO TO 11
VOLTKT=XHIGH2*PI*RADTK1**2
VOLTKG=XHIGH1*PI*RADTK1**2
GO TO 10
11 CONTINUE
THAT=2.*ATAN(SQRT(2.*XHIGH2*RADTK1-XHIGH2**2)/(RADTK1-XHIGH2))
VOLTKT=(TKLENG*RADTK1**2/2.)*(THAT-SIN(THAT))
THETAT=2.*ATAN(SQRT(2.*XHIGH1*RADTK1-XHIGH1**2)/(RADTK1-XHIGH1))
VOLTKG=(TKLENG*RADTK1**2/2.)*(THETAT-SIN(THETAT))
10 CONTINUE
VOLTKL=VOLTKT-VOLTKG
1 CONTINUE
C
D0109L=1,NJCT

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```

HT(L)=HT(L)-ELEV(L)

      IF(NSORCE(L).NE.2)GOTO109
C    ** FOR PUMP HEAD **
      DHEAD(L)=HT(L)
      J1=JJ(L,1)
      N1=N(J1)+1
      SHEAD(L)=H(J1,N1)-ELEV(L)
      HT1(L)=H(J1,N1)
109  CONTINUE
C
      IF (LTAPE.EQ. 0) GO TO 210
      MPTS=(TMAX-T)/(DELT*FLOAT(ITTPE))
      MPTS=MPTS-1
      WRITE (LTAPE) MPTS
210  CONTINUE
C
      CALL OUTPUT
      RETURN
      END
      SUBROUTINE STATE
C
C    ** ROUTINE FOR TRANSIENT CALCULATION **
C
      COMMON /IN1/ NP(30),NSORCE(30),NSINK(30),NSTANK(30),HT(30),
1 C1P(30),C2P(30),C3P(30),VOL(30),VOLMIN(30),GAMMA(30),KK(30),
2 C0(30),C4P(30),G(30),QP(30),FLI(30),DLI(30),XLI(30),VOLMAX(30)
      COMMON /INA/ D(40),XL(40),VO(40),A(40),ALPHA(40),F(40),FF(40)
      COMMON /IN2/C44(30),CV(30),IC(30,5),JJ(30,5),NTAU(30),TIME(10,30),
1 TAU(10,30),TMD(10),TAUD(10)
      COMMON /IN3/ NJCT,NPIPE,DELT,T,TMAX,ITPRNT,ISTOP,LPRT,LPLT,
1 ITPLT,LTAPE,ITTPE,NJPLT,JPLT(30),TIME2,ITPR2,TIME3,ITPR3
2 ,TIME4,ITPR4
      COMMON /BK1/ XN(40),DELX(40),THETA(40),N(40),C1(40),C3(40),C2(40),
1H1M(40),HNM(40),T1(40),TN(40),HT1(30),DHEAD(30),SHEAD(30),ELEV(30)
      COMMON /BK2/ V(40,200),H(40,200),VS(40,200),HS(40,200),
1VR(40,200),VD(40,200),
1 HR(40,200),VP(40,200),HP(40,200),XIC(30,5),C(30,5)
      COMMON /BK3/ G,PI,RHO,VARPR,TITLE(20),ITCTR,KNTAPE,IRUN
1 ,ISTART,IDATPE
      COMMON /BUBBL/ VDP(40,200),XCAV(40,200),CAVL(40),NCAV(40),HST(40)
      COMMON /TANK/ ITANK1,RADTK1,XHIGH1,XHIGH2,XDIST,VOLTKT,VOLTKG,
1 VOLTKL,VFLOIN,TKLENG
C
      T=T+DELT
      DO10J=1,NPIPE
      THETA(J)=DELT/DELX(J)
      NN=N(J)
      DO10I=1,NN
      VR(J,I)=(V(J,I+1)-THETA(J)*A(J)*(V(J,I+1)-V(J,I)))/(1.+THETA(J)*(V
1(J,I+1)-V(J,I)))
      VS(J,I+1)=(V(J,I)-THETA(J)*A(J)*(V(J,I)-V(J,I+1)))/(1.-THETA(J)*(V
1(J,I)-V(J,I+1)))
      HR(J,I)=H(J,I+1)-THETA(J)*(VR(J,I)+A(J))*(H(J,I+1)-H(J,I))
      HS(J,I+1)=H(J,I)+THETA(J)*(VS(J,I+1)-A(J))*(H(J,I)-H(J,I+1))
10  CONTINUE
C
C    ** FOR INTERIOR POINTS **
      DO11J=1,NPIPE
      IF(CAVL(J).LT.XL(J)) GO TO 13
      FF(J)=0.
      GO TO 14

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13   FF(J)=F(J)*(XL(J)-CAVL(J))/XL(J)

14   NN=N(J)-1
      IF(NN.EQ.0)GOTO11
      DO110I=1,NN
        VP(J,I+1)=0.5*(VR(J,I)+VS(J,I+2)+C2(J)*(HR(J,I)-HS(J,I+2)-DELT*SIN
1  (ALPHA(J))*(VR(J,I)-VS(J,I+2)))-(FF(J)*DELT/(2.*D(J))*(VR(J,I)*
2  ABS(VR(J,I))+VS(J,I+2)*ABS(VS(J,I+2))))
        HP(J,I+1)=0.5*(HR(J,I)+HS(J,I+2)+(A(J)/G)*(VR(J,I)-VS(J,I+2))-DELT
1  *SIN(ALPHA(J))*(VR(J,I)+VS(J,I+2))-(A(J)/G)*(FF(J)*DELT/(2.*D(J))*
2  *(VR(J,I)*ABS(VR(J,I))-VS(J,I+2)*ABS(VS(J,I+2))))
110  CONTINUE
11   CONTINUE
C
C   ** FOR CALCULATION OF BOUNDARY POINTS **
      DO12J=1,NPIPE
        I=1
        IF(XCAV(J,I).NE.0.)VS(J,I+1)=V(J,I+1)
        C1(J)=VS(J,I+1)*(1.+C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*ABS(VS(J,I
1  +1))/(2.*D(J)))-C2(J)*HS(J,I+1)
        I=N(J)
        IF(XCAV(J,I).NE.0.)VR(J,I)=VD(J,I)
12   C3(J)=VR(J,I)*(1.-C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*ABS(VR(J,I))
1  /(2.*D(J))+C2(J)*HR(J,I)
C
      RETURN
      END
      SUBROUTINE BOUDRY
C
C   ** ROUTINE FOR BOUNDARY CONDITIONS **
C
      COMMON /IN1/ NP(30),NSORCE(30),NSINK(30),NSTANK(30),HT(30),
1  C1P(30),C2P(30),C3P(30),VOL(30),VOLMIN(30),GAMMA(30),KK(30),
2  CO(30),C4P(30),Q(30),GP(30),FLI(30),DLI(30),XLI(30),VOLMAX(30)
      COMMON /INA/ D(40),XL(40),VO(40),A(40),ALPHA(40),F(40),FF(40)
      COMMON /IN2/ C44(30),CV(30),IC(30,5),JJ(30,5),NTAU(30),TIME(10,30),
1  TAU(10,30),TMD(10),TAUD(10)
      COMMON /IN3/ NJCT,NPIPE,DELT,T,TMAX,ITPRNT,ISTOP,LPRT,LPLT,
1  ITPLT,LTAPE,ITTPE,NJPLT,JPLT(30),TIME2,ITPR2,TIME3,ITPR3
2  ,TIME4,ITPR4
      COMMON /BK1/ XN(40),DELX(40),THETA(40),N(40),C1(40),C3(40),C2(40),
1  H1M(40),HNM(40),T1(40),TN(40),HT1(30),DHEAD(30),SHEAD(30),ELEV(30)
      COMMON /BK2/ V(40,200),H(40,200),VS(40,200),HS(40,200),
1  VR(40,200),VD(40,200),
1  HR(40,200),VP(40,200),HP(40,200),XIC(30,5),C(30,5)
      COMMON /BK3/ G,PI,RHO,VARPR,TITLE(20),ITCTR,KNTAPE,IRUN
1  ,ISTART,IDATPE
      COMMON /BUBBL/ VDP(40,200),XCAV(40,200),CAVL(40),NCAV(40),HST(40)
      COMMON /TANK/ ITANK1,RADTK1,XHIGH1,XHIGH2,XDIST,VOLTKT,VOLTKG,
1  VOLTKL,VFLOIN,TKLENG
C
      DO13L=1,NJCT
      IF(NSINK(L).NE.0)GOTO27
      IF(IABS(NSORCE(L)).EQ.1.OR.NSORCE(L).EQ.3)GO TO 101
      IF(NSORCE(L).EQ.2)GOTO19
C
C   ** FOR NSORCE(L)=0,4,5,ECT. **
      NL=NP(L)
      SUMD2=0.
      SUMDEN=0.
      SUMNUM=0.
      DO14M=1,NL

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J=JJ(L,M)

XIC(L,M)=IC(L,M)
IF(IC(L,M).GT.0)GOTO15
C(L,M)=C1(J)*XIC(L,M)
GOTO16
15 C(L,M)=C3(J)*XIC(L,M)
16 SUMD2=SUMD2+D(J)**2
SUMDEN=SUMDEN+C2(J)*D(J)**2
14 SUMNUM=SUMNUM+C(L,M)*D(J)**2
HT(L)=SUMNUM/SUMDEN
IF(HT(L).LE.VARPR) HT(L)=VARPR
IF(NSTANK(L).NE.0)GOTO23
26 DO17M=1,NL
J=JJ(L,M)
IF(IC(L,M).LT.0)GOTO18
I=N(J)+1
HP(J,I)=HT(L)
VP(J,I)=C3(J)-C2(J)*HP(J,I)
GOTO17
18 I=1
HP(J,I)=HT(L)
VP(J,I)=C1(J)+C2(J)*HP(J,I)
17 CONTINUE
GOTO13

C
C ** SURGE TANK AT JUNCTION **
23 J=JJ(L,1)
J1=JJ(L,2)
I=1
NN=N(J)+1
HBAR=30.8
KIT=10
A1=(PI/4.)*D(J)**2
A2=(PI/4.)*D(J1)**2
A12=(PI/4.)*DLI(L)**2
B1=A1*C3(J)-A2*C1(J1)
D1=A1*C2(J)+A2*C2(J1)
IF(NSTANK(L).GT.1) GO TO 411
IF(XLI(L).NE.0.) GO TO 413
E1=0.
E2=0.
GO TO 414
413 C22=2.*XLI(L)/(G*A12*DELT)
C11=HST(L)-H(J,NN)+FLI(L)*XLI(L)*G(L)*ABS(G(L))/(G*
1 DLI(L)*A12**2)-C22*G(L)
E1=C22*D1
E2=-C11-C22*B1

C
C SURGE TANK OR AIR CHAMBER ( IF XLI(L)=0 )
C
414 DO410 II=1,KIT
VOLP=VOL(L)-.5*DELT*(GP(L)+G(L))
IF(VOLP.LT.VOLMIN(L)) VOLP=VOLMIN(L)
IF(VOLP.GT.VOLMAX(L)) VOLP=VOLMAX(L)
F1=((1.+E1)*(B1-GP(L))/D1+E2+HBAR-ELEV(L))*
1 VOLP**GAMMA(L)-CD(L)
DFDG=-GAMMA(L)*DELT*CD(L)*.5/VOLP-(VOLP**GAMMA(L))
1 *(1.+E1)/D1
DQ=-F1/DFDG
410 GP(L)=GP(L)+DQ
VOL(L)=VOL(L)-.5*DELT*(GP(L)+G(L))

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IF(VOL(L).LT.VOLMIN(L)) VOL(L)=VOLMIN(L)

IF(VOL(L).GT.VOLMAX(L)) VOL(L)=VOLMAX(L)
HST(L)=(E1+1.)*(B1-GP(L))/D1+E2
HT(L)=(B1-GP(L))/D1
GO TO 409

C
C      LUMPED INERTIA
C
411  CONTINUE
      IF (NSTANK(L).GT.2) GO TO 412
      C22=2.*XLI(L)/(G*A12*DELT)
      C11=H(J1,I)-H(J,NN)+FLI(L)*XLI(L)*G(L)*ABS(G(L))/
1 (G*DLI(L)*A12**2)-C22*G(L)
      GP(L)=((C3(J)/C2(J))+(C1(J1)/C2(J1))-C11)/(C22+
1 (1./(A1*C2(J)))+(1./(A2*C2(J1))))
      VP(J,NN)=GP(L)/A1
      VP(J1,I)=GP(L)/A2
      HP(J,NN)=(C3(J)-VP(J,NN))/C2(J)
      HP(J1,I)=(VP(J1,I)-C1(J1))/C2(J1)
      G(L)=GP(L)
      GO TO 13

C
C      LUMPED CAPACITANCE
C
412  KA=.5*KK(L)*DELT/(VOL(L)*RHO)
      GP(L)=((H(J,NN)+KA*G(L))*(-D1)+B1)/(1.+KA*D1)
      VOL(L)=VOL(L)+.5*DELT*(GP(L)+G(L))
      HT(L)=H(J,NN)+KA*(GP(L)+G(L))
409  G(L)=GP(L)
      VP(J,NN)=C3(J)-C2(J)*HT(L)
      VP(J1,I)=C1(J1)+C2(J1)*HT(L)
      HP(J,NN)=HT(L)
      HP(J1,I)=HT(L)
415  GO TO 13

C
C      PUMP BETWEEN TWO PIPES OF EQUAL DIAMETER
19  J=JJ(L,1)
      J1=JJ(L,2)
      I=N(J)+1
      IABORT=19
      IF((C1P(L).EQ.0.).AND.(C3P(L).EQ.0.))GOTO51
      IF((C2P(L).EQ.0.).AND.(C3P(L).EQ.0.))GOTO51
      IF(C3P(L).EQ.0.)GOTO51
      AA=C1P(L)
      BB=C2P(L)-1./C2(J)-1./C2(J1)
      CC=C3(J)/C2(J)+C1(J1)/C2(J1)+C3P(L)
      VP(J,I)=(-BB-SQRT(ABS(BB**2-4.*AA*CC)))/(2.*AA)
      IF(VP(J,I).LE.0.)VP(J,I)=0.
      VP(J1,I)=VP(J,I)
      HP(J,I)=(VP(J,I)-C3(J))/(-C2(J))
      HP(J1,I)=(VP(J1,I)-C1(J1))/C2(J1)
      SHEAD(L)=HP(J,I)-ELEV(L)
      DHEAD(L)=HP(J1,I)-ELEV(L)
      HT(L)=HP(J1,I)
      GOTO13

C
C      PUMP OR RESERVOIR AT END OF PIPE
101 M=1
      J=JJ(L,M)
      I=1
      IF (NSORCE(L).EQ.(-1)) I=N(J)+1

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IABORT=101

IF((C1P(L).EQ.0.).AND.(C3P(L).EQ.0.))GOTO51
IF((C2P(L).EQ.0.).AND.(C3P(L).EQ.0.))GOTO51
IF(C3P(L).EQ.0.)GOTO51
IF(C1P(L).EQ.0.)GOTO20
AA=C1P(L)*C2(J)
BB=C2P(L)*C2(J)-1.
CC=C3P(L)*C2(J)+C1(J)
VP(J,I)=(-BB-SQRT(BB**2-4.*AA*CC))/(2.*AA)
IF(VP(J,I).LE.0.)VP(J,I)=0.
GOTO22
20 IF(C2P(L).EQ.0.)GOTO21
VP(J,I)=(C3P(L)-(C1(J)/C2(J)))/(C2P(L)+1./C2(J))
IF(VP(J,I).LE.0.)VP(J,I)=0.
GOTO22
21 CONTINUE
VP(J,I)=C1(J)+C2(J)*C3P(L)
IF(NSORCE(L).EQ.(-1))VP(J,I)=C3(J)-C2(J)*C3P(L)
IF(NSORCE(L).EQ.3)GOTO111
C
C FOR PUMP BETWEEN TWO PIPES THIS IS HEAD INCREASE
22 HT(L)=C1P(L)*VP(J,I)**2+C2P(L)*VP(J,I)+C3P(L)
IF (HT(1) .LT. 0.) HT(1)=0.
HP(J,I)=HT(L)
GOTO13
C
C RESERVOIR WITH CHECK VALVE TO PREVENT BACK FLOW ... ALSO SIMULATES
C HYDROPNEUMATIC TANK WITH CONSTANT GAS BLANKET PRESSURE
111 IF(VP(J,I).LE.0.)VP(J,I)=0.
HP(J,I)=(VP(J,I)-C1(J))/C2(J)
HT(L)=HP(J,I)
GOTO 13
C
C ** FOR VALVES **
27 NV=NSINK(L)
M=1
J=JJ(L,M)
I=N(J)+1
IPASS=1
IABORT=27
IF(NV.GT. 2) GO TO 81
NTAB=NTAU(L)
DO 80 K=1,NTAB
TMD(K)=TIME(K,L)
TAUD(K)=TAUV(K,L)
80 CONTINUE
CALL INTP(T,TAU,NTAB,TMD,TAUD)
GO TO 28
81 IF (NV.GT. 7) GO TO 51
TAU=1.
28 C4=C44(L) *TAU**2
GO TO (37,36,37,36,37,37,36),NV
C
C VALVE OR DRIFICE AT END OF PIPE DISCHARGING TO ATMOSPHERE
36 VP(J,I)=-C4/2.+SQRT(ABS((C4/2.）**2+C3(J)*C4))
HP(J,I)=(C3(J)-VP(J,I))/C2(J)
IF (HP(J,I) .LE. ELEV(L)) GO TO 116
IF (NV.EQ. 7) GO TO 104
GO TO 105
116 HP(J,I)=ELEV(L)
VP(J,I)=C3(J)-C2(J)*ELEV(L)

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105  HT(L)=HP(J,I)

      GOTD13
C
C  PRESSURE RELIEF VALVE
104  XVALVE=C1P(L)
      IF(HP(J,I).LE.XVALVE)VP(J,I)=0.
      HP(J,I)=(C3(J)-VP(J,I))/C2(J)
      GOTD105
C
C  VALVE OR ORIFICE BETWEEN TWO PIPES OF EQUAL DIAMETER
37   J1=JJ(L,M+1)
      I1=1
      C1PC3=C1(J1)+C3(J)
      IF((C1PC3.GE.0.).AND.(TAU.GT..00001))GO TO 38
      IF (NV.EQ. 5) TAU=0.0
      IF(TAU.LT..00001)GO TO 39
C
C  NEGATIVE FLOW THRU VALVE OR ORIFICE
      VP(J,I)=C4-SQRT(C4**2-C4*C1PC3)
48   VP(J1,I1)=VP(J,I)
      HP(J,I)=(C3(J)-VP(J,I))/C2(J)
      HP(J1,I1)=(VP(J1,I1)-C1(J1))/C2(J1)
      HT(L)=HP(J,I)
      HT1(L)=HP(J1,I1)
      IF (IPASS.EQ. 2) GO TO 13
C
C  C1P(L) BELOW IS HEAD AT WHICH PRESSURE REDUCING VALVE IS ACTIVATED
      IF((NV.EQ. 6).AND.(HP(J1,I1).GE.C1P(L))) GO TO 115
      GOTD13
C
C  POSITIVE FLOW THRU VALVE OR ORIFICE
38   VP(J,I)=-C4+SQRT(C4**2+C4*C1PC3)
      GOTD48
39   VP(J,I)=0.
      GO TO 48
115  IPASS=2
C
C  C2P(L) BELOW IS HEAD AT WHICH PRESSURE REDUCING VALVE IS COMPLETEL
C  CLOSED
      TAU=((C2P(L)-HP(J1,I1))/(C2P(L)-C1P(L)))**2
      IF (HP(J1,I1).GE. C2P(L)) TAU=0.
      C4=C44(L) *TAU**2
      GO TO 37
13   CONTINUE
      RETURN
C
51   WRITE (6,52) IABORT
52   FORMAT (1X,'SOLUTION TERMINATED DUE TO BAD DATA'//
1 1X,'IABORT=',I5,2X,'IN BOUNDARY')
      STOP
      END
      SUBROUTINE PHASE
C
C  ** ROUTINE FOR PHASE **
C
      COMMON /IN1/ NP(30),NSORCE(30),NSINK(30),NSTANK(30),HT(30),
1 C1P(30),C2P(30),C3P(30),VOL(30),VOLMIN(30),GAMMA(30),KK(30),
2 CO(30),C4P(30),Q(30),QP(30),FLI(30),DLI(30),XLI(30),VOLMAX(30)
      COMMON /INA/ D(40),XL(40),VO(40),A(40),ALPHA(40),F(40),FF(40)
      COMMON /IN2/C44(30),CV(30),IC(30,5),JJ(30,5),NTAU(30),TIME(10,30),
1 TAUUV(10,30),TMD(10),TAUD(10)

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COMMON /IN3/ NJCT,NPIPE,DELT,T,TMAX,ITPRNT,ISTOP,LPRT,LPLT,
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1 ITPLT,LTAP,ITTPE,NJPLT,JPLT(30),TIME2,ITPR2,TIME3,ITPR3
2 ,TIME4,ITPR4
COMMON /BK1/ XN(40),DELX(40),THETA(40),N(40),C1(40),C3(40),C2(40),
1H1M(40),HNM(40),T1(40),TN(40),HT1(30),DHEAD(30),SHEAD(30),ELEV(30)
COMMON /BK2/ V(40,200),H(40,200),VS(40,200),HS(40,200),
1VR(40,200),VD(40,200),
1 HR(40,200),VP(40,200),HP(40,200),XIC(30,5),C(30,5)
COMMON /BK3/ G,P,I,RHD,VARPR,TITLE(20),ITCTR,KNTAPE,IRUN
1 ,ISTART,IDATPE
COMMON /BUBBL/ VDP(40,200),XCAV(40,200),CAVL(40),NCAV(40),HST(40)
COMMON /TANK/ ITANK1,RADTK1,XHIGH1,XHIGH2,XDIST,VOLTKT,VOLTKG,
1 VOLTKL,VFLOIN,TKLENG
```

C

```
DO40L=1,NJCT
NL=NP(L)
DO112M=1,NL
IF(IC(L,M).GT.0)GOTO112
J=JJ(L,M)
NN=N(J)+1
CAVL(J)=0.
NCAV(J)=0
DO 115 I=1,NN
X=I-1
ELJI=ELEV(L)-X*DELX(J)*SIN(ALPHA(J))
VAPHJI=ELJI+VARPR
IF(I.EQ.1) GO TO 509
IF(I.NE.NN) GO TO 508
509 IF(HP(J,I).GE.VAPHJI)GOTO501
HP(J,I)=VAPHJI
GOTO501
```

C

C

```
LIQUID FLOW WITH GAS BUBBLE
508 IF((XCAV(J,I-1).EQ.0.)AND.(XCAV(J,I+1).EQ.0.)) GO TO 500
VCP=VD(J,I-1)*(1.-C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*
1ABS(VD(J,I-1)))/(2
2.*D(J))+C2(J)*H(J,I-1)
VCM=V(J,I+1)*(1.+C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*ABS(V(J,I+1
1)))/(2.*D(J))-C2(J)*H(J,I+1)
IF(XCAV(J,I).GT.0.) GO TO 401
HP(J,I)=.5*(VCP-VCM)/C2(J)
IF(HP(J,I).GE.VAPHJI) GO TO 502
GO TO 401
500 IF(XCAV(J,I).GT.0.) GO TO 402
IF(HP(J,I).GE.VAPHJI) GO TO 501
402 VCP=VR(J,I-1)*(1.-C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*ABS(VR(J,I-1
1)))/(2.*D(J))+C2(J)*HR(J,I-1)
VCM=VS(J,I+1)*(1.+C2(J)*DELT*SIN(ALPHA(J))-FF(J)*DELT*ABS(VS(J,I+1
1)))/(2.*D(J))-C2(J)*HS(J,I+1)
401 HP(J,I)=VAPHJI
VP(J,I)=VCP-C2(J)*HP(J,I)
VDP(J,I)=VCM+C2(J)*HP(J,I)
XCAV(J,I)=XCAV(J,I)+.5*DELT*(VDP(J,I)+VD(J,I)-VP(J,I)-V(J,I))
NCAV(J)=NCAV(J)+1
IF(XCAV(J,I).GT.0.)GOTO503
XCAV(J,I)=0.
HP(J,I)=VAPHJI+.25*(VP(J,I)+V(J,I)-VDP(J,I)-VD(J,I))/C2(J)
NCAV(J)=NCAV(J)-1
502 VP(J,I)=VCP-C2(J)*HP(J,I)
501 VDP(J,I)=VP(J,I)
503 V(J,I)=VP(J,I)
```



```

VD(J,I)=VDP(J,I)

H(J,I)=HP(J,I)
CAVL(J)=CAVL(J)+XCAV(J,I)
HP(J,I)=HP(J,I)-ELJI
IF (HP(J,I) .LE. VARPR) HP(J,I)=VARPR
115 CONTINUE
112 CONTINUE
40 CONTINUE
DO43J=1,NPIPE
I=1
NN=N(J)+1
IF (H1M(J).GE. HP(J,I)) GOTO 41
H1M(J)=HP(J,I)
T1(J)=T
41 IF (HNM(J).GE. HP(J,NN)) GOTO 42
HNM(J)=HP(J,NN)
TN(J)=T
42 CONTINUE
43 CONTINUE
DO50L=1,NJCT
VAPHTL=ELEV(L)+VARPR
HT(L)=HT(L)-ELEV(L)
IF (HT(L) .LE. VAPHTL) HT(L)=VARPR
50 CONTINUE
RETURN
END
SUBROUTINE OUTPUT
C
C ** ROUTINE TO OUTPUT TRANSIENT SOLUTION **
C
COMMON /IN1/ NP(30),NSORCE(30),NSINK(30),NSTANK(30),HT(30),
1 C1P(30),C2P(30),C3P(30),VOL(30),VOLMIN(30),GAMMA(30),KK(30),
2 CD(30),C4P(30),Q(30),QP(30),FLI(30),DLI(30),XLI(30),VOLMAX(30)
COMMON /INA/ D(40),XL(40),VO(40),A(40),ALPHA(40),F(40),FF(40)
COMMON /IN2/ C44(30),CV(30),IC(30,5),JJ(30,5),NTAU(30),TIME(10,30),
1 TAU(10,30),TMD(10),TAUD(10)
COMMON /IN3/ NJCT,NPIPE,DELT,T,TMAX,ITPRNT,ISTOP,LPRT,LPLT,
1 ITPLT,LTAPE,ITTPE,NJPLT,JPLT(30),TIME2,ITPR2,TIME3,ITPR3
2 ,TIME4,ITPR4
COMMON /BK1/ XN(40),DELX(40),THETA(40),N(40),C1(40),C3(40),C2(40),
1 H1M(40),HNM(40),T1(40),TN(40),HT1(30),DHEAD(30),SHEAD(30),ELEV(30)
COMMON /BK2/ V(40,200),H(40,200),VS(40,200),HS(40,200),
1 VR(40,200),VD(40,200),
1 HR(40,200),VP(40,200),HP(40,200),XIC(30,5),C(30,5)

```



```

COMMON /BK3/ G,PI,RHO,VARPR,TITLE(20),ITCTR,KNTAPE,IRUN
1 , ISTART, IDATPE
COMMON /BUBBL/ VDP(40,200),XCAV(40,200),CAVL(40),NCAV(40),HST(40)
COMMON /TANK/ ITANK1,RADTK1,XHIGH1,XHIGH2,XDIST,VOLTKT,VOLTKG,
1 VOLTKL,VFLOIN,TKLENG

C
  IF (LPRT .EQ. 0) GO TO 10
  IF (TIME2 .LE. 0.0) GO TO 77
  IF (T .GT. TIME2) ITPRNT=ITPR2
17  IF (TIME3 .LE. 0.0) GO TO 77
  IF (T .GT. TIME3) ITPRNT=ITPR3
  IF (TIME4 .LE. 0.0) GO TO 77
  IF (T .GT. TIME4) ITPRNT=ITPR4
77  CONTINUE
  IF (MOD(ITCTR,ITPRNT) .NE. 0) GO TO 10
  WRITE (6,4) T
4   FORMAT(1H1, ' SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME=',E15.5,
1 2X, 'SEC',/)
  WRITE (6,5)
5   FORMAT (1X, 'PIPE NO. ',6X, 'PRESSURE HEAD',7X, 'PRESSURE HEAD',
116X, 'VELOCITY',12X, 'VELOCITY',14X, 'VAPOR CAVITY',/15X,
2'UP STREAM END',7X, 'DN STREAM END',12X, 'UP STREAM END',7X,
3'DN STREAM END',16X, 'LENGTH',/20X, 'PSI',17X, 'PSI',21X, 'FT/SEC',
414X, 'FT/SEC',21X, 'FT',/)
  J=4
  OI=H1M(J)*RHO/144.
  TOI=T1(J)
  J=5
  SO=HNM(J)*RHO/144.
  TSO=TN(J)
  J=8
  SI=H1M(J)*RHO/144.
  TSI=T1(J)
  DO 8 J=1,NPIPE
  I=1
  NN=N(J)+1
  H1M(J)=HP(J,I)
  T1(J)=T
  HNM(J)=HP(J,NN)
  TN(J)=T
  HPIPSI=HP(J,I)*RHO/144.
  HPNPSI=HP(J,NN)*RHO/144.
  WRITE (6,9) J,HPIPSI,HPNPSI,VP(J,I),VP(J,NN),CAVL(J)
9   FORMAT (3X,I4,5X,E15.5,5X,E15.5,10X,E15.5,5X,E15.5,10X,
1 E15.5)
  IF(NCAV(J).EQ.0) GO TO 8
  WRITE(6,105) J,NCAV(J)
105  FORMAT(1X, 'NCAV(',I3,')=',I3,/)
8   CONTINUE
  WRITE(6,104) SI,TSI,SO,TSO,OI,TOI
104  FORMAT(/1X, 'MAXIMUM HEAD (PSI)'/1X, 'SKID INLET : ',
13X,E15.5,5X, 'AT T=',E15.5,5X, 'SEC'/1X, 'SKID OUTLET : ',
22X,E15.5,5X, 'AT T=',E15.5,5X, 'SEC'/1X, 'ORBITER INLET : ',
3E15.5,5X, 'AT T=',E15.5,5X, 'SEC')

C
  IF (ITANK1 .EQ. 0) GO TO 1
  IF (T .LE. 1.0E-10) GO TO 18
  WRITE (6,19)
19  FORMAT (/1X, 'DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED',/)
18  WRITE (6,2) VOLTKT,VOLTKG,VOLTKL,C3P(1),ELEV(1),XL(1),DELX(1)

```



```

2      FORMAT (/1X, 'VOLTKT, VOLT KG, VOLTKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE

1      1, RESPECTIVELY' /10X, 7E15. 5)
1      CONTINUE
C
      DO102L=1, NJCT
102     IF(NSORCE(L).EQ.2)WRITE(6,103)L, SHEAD(L), DHEAD(L)
103     FORMAT(1H0, 16HPUMP AT JUNCTION, I3, 5X, 13HSUCTION HEAD=, F8. 1, 5X, 15HD
1      1 ISCHARGE HEAD=, F8. 1)
C
10     IF (LTAPE .EQ. 0) GO TO 40
      IF (MOD(ITCTR, ITTPE) .NE. 0) GO TO 40
      WRITE (LTAPE) T, (HT(L), L=1, NJCT)
      DO 7 J=1, NPIPE
        NN=N(J)+1
7      WRITE (LTAPE) (HP(J, I), VP(J, I), I=1, NN)
      KNTAPE=KNTAPE+1
C
40     CONTINUE
      ITCTR=ITCTR+1
      RETURN
      END
      SUBROUTINE TMSTEP
C
C      ** ROUTINE TO CHECK TIME STEP FOR STABILITY **
C
      COMMON /IN1/ NP(30), NSORCE(30), NSINK(30), NSTANK(30), HT(30),
1      C1P(30), C2P(30), C3P(30), VOL(30), VOLMIN(30), GAMMA(30), KK(30),
2      CO(30), C4P(30), G(30), GP(30), FLI(30), DLI(30), XLI(30), VOLMAX(30)
      COMMON /INA/ D(40), XL(40), VO(40), A(40), ALPHA(40), F(40), FF(40)
      COMMON /IN2/ C44(30), CV(30), IC(30, 5), JJ(30, 5), NTAU(30), TIME(10, 30),
1      TAU(10, 30), TMD(10), TAU(10)
      COMMON /IN3/ NJCT, NPIPE, DELT, T, TMAX, ITPRNT, ISTOP, LPRT, LPLT,
1      ITPLT, LTAPE, ITTPE, NUPLT, JPLT(30), TIME2, ITPR2, TIME3, ITPR3
2      , TIME4, ITPR4
      COMMON /BK1/ XN(40), DELX(40), THETA(40), N(40), C1(40), C3(40), C2(40),
1      H1M(40), HNM(40), T1(40), TN(40), HT1(30), DHEAD(30), SHEAD(30), ELEV(30)
      COMMON /BK2/ V(40, 200), H(40, 200), VS(40, 200), HS(40, 200),
1      VR(40, 200), VD(40, 200),
1      HR(40, 200), VP(40, 200), HP(40, 200), XIC(30, 5), C(30, 5)
      COMMON /BK3/ G, PI, RHD, VARPR, TITLE(20), ITCTR, KNTAPE, IRUN
1      , ISTART, IDATPE
      COMMON /BUBBL/ VDP(40, 200), XCAV(40, 200), CAVL(40), NCAV(40), HST(40)
      COMMON /TANK/ ITANK1, RADTK1, XHIGH1, XHIGH2, XDIST, VOLTKT, VOLT KG,
1      VOLTKL, VFLOIN, TKLENG
C
      TOL=1.0E-6
      DTMIN=DELX(1)/(V(1, 1)+A(1))
      DO 1 J=1, NPIPE
        NN=N(J)+1
        DO 2 I=1, NN
          DTEST=DELX(J)/(V(J, I)+A(J))
          IF (DTMIN .LE. DTEST)GO TO 10
          DTMIN=DTEST
        JM=J
10     IF (DTMIN .GT. TOL) GO TO 2
      WRITE (6, 9) J, I, DELX(J), V(J, I), A(J), DTMIN
9     FORMAT (/1X, 'TIME STEP TOO SMALL---J, I, DELX(J), V(J, I), A(J), DTMIN' /
1      11X, 2I10, 4E20. 5)
      LPRT=1
      ITPRNT=1
      CALL OUTPUT

```


STOP

```

2    CONTINUE
1    CONTINUE
8    IF (DELT .GT. DTMIN) GO TO 4
    RETURN
4    DELT=DELT/2.
    ITPRNT=2*ITPRNT
    ITPLT=2*ITPLT
    ITTPE=2*ITTPE
    ITPR2=2*ITPR2
    ITPR3=2*ITPR3
    ITPR4=2*ITPR4
    WRITE (6,5) DELT,JM
5    FORMAT (/1X, 'TIME STEP HAS BEEN HALVED, DELT=', E15.6, '
1    AT PIPE ', I2, /)
    GO TO 8
    END
    SUBROUTINE  TMFUNC
C
C    ROUTINE FOR TANK AT JUNCTION ONE
C
    DIMENSION XC(11),FX(11),XI(18),FD(18)
C
    COMMON /IN1/ NP(30),NSORCE(30),NSINK(30),NSTANK(30),HT(30),
1    C1P(30),C2P(30),C3P(30),VOL(30),VOLMIN(30),GAMMA(30),KK(30),
2    CO(30),C4P(30),G(30),GP(30),FLI(30),DLI(30),XLI(30),VOLMAX(30)
    COMMON /INA/ D(40),XL(40),VO(40),A(40),ALPHA(40),F(40),FF(40)
    COMMON /IN2/ C44(30),CV(30),IC(30,5),JJ(30,5),NTAU(30),TIME(10,30),
1    TAU(10,30),TMD(10),TAUD(10)
    COMMON /IN3/ NJCT,NPIPE,DELT,T,TMAX,ITPRNT,ISTOP,LPRT,LPLT,
1    ITPLT,LTAPE,ITTPE,NJPLT,JPLT(30),TIME2,ITPR2,TIME3,ITPR3
2    ,TIME4,ITPR4
    COMMON /BK1/ XN(40),DELX(40),THETA(40),N(40),C1(40),C3(40),C2(40),
1    H1M(40),HNM(40),T1(40),TN(40),HT1(30),DHEAD(30),SHEAD(30),ELEV(30)
    COMMON /BK2/ V(40,200),H(40,200),VS(40,200),HS(40,200),
1    VR(40,200),VD(40,200),
1    HR(40,200),VP(40,200),HP(40,200),XIC(30,5),C(30,5)
    COMMON /BK3/ G,PI,RHD,VARPR,TITLE(20),ITCTR,KNTAPE,IRUN
1    ,ISTART,IDATPE
    COMMON /BUBBL/ VDP(40,200),XCAV(40,200),CAVL(40),NCAV(40),HST(40)
    COMMON /TANK/ ITANK1,RADTK1,XHIGH1,XHIGH2,XDIST,VOLTKT,VOLTKG,
1    VOLTKL,VFLOIN,TKLENG
C
C    DATA FOR SPHERICAL TANK
C    DATA KN,XC,FX/11,0.,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,0.,
1    0.028,0.104,0.216,0.352,0.5,0.648,0.784,0.896,0.972,1.0/
C
C    DATA FOR HORIZONTAL CYLINDRICAL TANK
C    DATA KM,XI,FD /18,0.,0.01,0.08,0.27,0.6,1.09,1.72,2.47,3.14,3.26,
1    4.04,4.76,5.35,5.8,6.08,6.23,6.26,6.28, 0.,0.4,0.8,1.2,1.6,2.0,
2    2.4,2.8,3.1416,3.2,3.6,4.0,4.4,4.8,5.2,5.6,6.0,6.28/
C
C    ITANK1=1 FOR SPHERICAL TANK, =2 FOR VERTICAL CYLINDRICAL TANK,
C    =3 FOR HORIZONTAL CYLINDRICAL TANK
C
    FLOUT=VP(1,1)*DELT*PI*D(1)**2/4.-VFLOIN
    IF (XDIST-XHIGH2)4,3,3
4    VOLTKG=VOLTKG+FLOUT
    VOLTKL=VOLTKT-VOLTKG
    IF (ITANK1.NE. 1) GO TO 5
    VRATIO=VOLTKG/VOLTKT

```



```

CALL INTP (VRATIO,XANS,KN,FX,XC)

XDISTO=XDIST
XDIST=2.*RADTK1* XANS
DDIST=XDIST-XDISTO
GO TO 6
5 IF (ITANK1 .NE. 2) GO TO 7
DDIST=FLOUT/(PI*RADTK1**2)
XDIST=XDIST+DDIST
GO TO 6
7 CONTINUE
VRATIO=2.*VOLTKG/(TKLENG*RADTK1**2)
CALL INTP (VRATIO,XANS,KM,XI,FD)
XDISTO=XDIST
XDIST=RADTK1*(1.-COS(0.5*XANS))
DDIST=XDIST-XDISTO
6 CONTINUE
C3P(1)=C3P(1)-DDIST
RETURN
C
3 DDIST=VP(1,1)*DELT
XL(1)=XL(1)-DDIST
XN(1)=N(1)
DELX(1)=XL(1)/XN(1)
ELEV(1)=ELEV(1)-DDIST*SIN(ALPHA(1))
C3P(1)=C3P(1)-DDIST*SIN(ALPHA(1))
RETURN
END
SUBROUTINE INTP (X,Y,NN,A,B)
DIMENSION A(1),B(1)
C
C ** ROUTINE FOR LINEAR INTERPOLATION **
C ** ARRAY A MUST BE IN ASCENDING ORDER **
C
C TO CHECK IF X IS WITHIN TABULATED RANGE
C SET Y EQUAL TO END-VALUE IF X IS OUT OF RANGE
C
IF (X .GT. A(1)) GO TO 10
Y=B(1)
RETURN
10 IF (X .LT. A(NN)) GO TO 20
Y=B(NN)
RETURN
20 CONTINUE
C
C TO FIND X1 AND Y1
C
DO 30 I=1,NN
IM1=I-1
TEST=X-A(NN-IM1)
IF (TEST) 30,34,38
38 X1=A(NN-IM1)
Y1=B(NN-IM1)
GO TO 40
34 Y=B(NN-IM1)
RETURN
30 CONTINUE
40 CONTINUE
C
C TO FIND X2 AND Y2
C
DO 50 I=1,NN

```


TEST=X-A(I)

```
      IF (TEST .GT. 0.) GO TO 50
      X2=A(I)
      Y2=B(I)
      GO TO 60
50     CONTINUE
60     CONTINUE
C
C     TO PERFORM LINEAR INTERPOLATION
C
      Y=Y1-(Y1-Y2)*(X1-X)/(X1-X2)
      RETURN
      END
      SUBROUTINE PLOTT
C
C     ** ROUTINE TO PLOT TRANSIENT SOLUTIONS ON SC4460 **
C
      RETURN
      END
```



```

VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]

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```

U  U  CCCC  FFFF
U  U  C    F
U  U  C    F
U  U  C    FFFF
U  U  C    F
U  U  C    F
UUUUU  CCCC  F

```

```

HH  HH  YY  YY  TTTTTTTTTT  RRRRRRRR  AAAAAA  NN  NN
HH  HH  YY  YY  TTTTTTTTTT  RRRRRRRR  AAAAAA  NN  NN
HH  HH  YY  YY  TT  RR  RR  AA  AA  NN  NN
HH  HH  YY  YY  TT  RR  RR  AA  AA  NN  NN
HH  HH  YY  YY  TT  RR  RR  AA  AA  NNNN  NN
HH  HH  YY  YY  TT  RR  RR  AA  AA  NNNN  NN
HHHHHHHHHH  YY  TT  RRRRRRRR  AA  AA  NN  NN  NN
HHHHHHHHHH  YY  TT  RRRRRRRR  AA  AA  NN  NN  NN
HH  HH  YY  TT  RR  RR  AAAAAAAAAA  NN  NNNN
HH  HH  YY  TT  RR  RR  AAAAAAAAAA  NN  NNNN
HH  HH  YY  TT  RR  RR  AA  AA  NN  NN
HH  HH  YY  TT  RR  RR  AA  AA  NN  NN
HH  HH  YY  TT  RR  RR  AA  AA  NN  NN

```

```

DDDDDDDD  AAAAAA  TTTTTTTTTT  1111  11  000000
DDDDDDDD  AAAAAA  TTTTTTTTTT  1111  11  000000
DD  DD  AA  AA  TT  1111  1111  00  00
DD  DD  AA  AA  TT  1111  1111  00  00
DD  DD  AA  AA  TT  11  00  0000
DD  DD  AA  AA  TT  11  00  0000
DD  DD  AA  AA  TT  1111  11  00  00  00
DD  DD  AA  AA  TT  1111  11  00  00  00
DD  DD  AAAAAAAAAA  TT  1111  11  0000  00
DD  DD  AAAAAAAAAA  TT  1111  11  0000  00
DD  DD  AA  AA  TT  11  00  00
DD  DD  AA  AA  TT  11  00  00
DD  DD  AA  AA  TT  11  00  00
DDDDDDDD  AA  AA  TT  111111  000000
DDDDDDDD  AA  AA  TT  111111  000000

```

```

U  U  CCCC  FFFF
U  U  C    F
U  U  C    F
U  U  C    FFFF
U  U  C    F
U  U  C    F
UUUUU  CCCC  F

```

```

VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]
VAX/VMS  UCF      HYTRAN  6-JUL-1983 16:38  LPA0:   6-JUL-1983 16:38  DISK$VAXVMSRL3:[UCF]

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HYTRAN. DAT; 10

6-JUL-1983 16:38

Page 1

LOX PRESSURE SPIKES WITHOUT VAPOR CAVITY COLLAPSE

*DIN

NJCT=22,

NPIPE=22,

DELT=0.0025,

TMAX=5.,

NP=1, 11*2, 3, 3*2, 3, 4*2, 1,

NSORCE=1,

NSINK=2*0, 2*3, 0, 3, 0, 1, 3*0, 3, 0, 2*1, 3, 0, 5, 0, 3, 0, 4,

NSTANK=4*0, 1, 0, 2,

HT=246.7, 246.7, 246.2, 232.6, 232.0, 228.1, 228., 223.9, 206.5, 202.6, 168.4, 68., 67.4,

66.9, 67.3, 65., 65., 55.9, 54.1, 53.2, 2*53.2,

C3P=246.7,

VDL=4*0., .83, 0., .5,

VOLMIN=4*0., .001, 0.,

VOLMAX=4*0., 2.7, 0.,

GAMMA=4*0., 1.4, 0.,

CO=4*0., 131.7, 0.,

XLI=4*0., 30., 0., 24.,

DLI=4*0., 0.166, 0., .5,

FLI=4*0., 0.01, 0., 0.02,

KK=4*0., 0., 0., 0.,

D=1.416, 5*.667, 8*.5, 3*.25, 2*.5, 2*1.0, 30.,

XL=103., 5.1, 10.2, 25.5, 94.5, 6.3, 26.2, 183.4, 39.3, 366.8, 1061.1, 7*6.55, 19.65,

6.125, 30.625, 34.75,

VO=2.307, 5*10.42, 6*18.52, 2*17.9, 3*2.47, 2*18.52, 2*4.63,

0.005,

A=2410., 3*1000., 2*2500., 13*2585., 3*2440.,

ALPHA=-70.51, 2*-21.87, -90., -3.7, 0., -6.57, 0., -90., -5.11, -0.124, 30.25,

5*0., -27.26, 2*0., 10.25, 90.,

JJ=1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 14, 18, 19, 20, 21, 22, 8*0

0, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 9*0,

12*0, 15, 3*0, 17,

IC=-1.21*1, 9*0, 20*-1, 21*0, -1, 3*0, 1,

CV=2*0., 3500., 680.3, 0., 1800., 0., 2000., 3*0., 2000., 0., 2000., 500., 60., 0., 850.,

0., 2530.7, 0., 4500000.,

ELEV=222.4, 125.3, 123.4, 119.6, 94.1, 2*88., 2*85., 45.7, 13., 10.7, 5*14., 3*11.,

16.45, 51.2,

N=17, 2, 4, 10, 15, 1, 4, 28, 6, 56, 162, 7*1, 3, 1, 5, 5,

F=22*0.0088,

NTAU=7*0, 10, 5*0, 2*10,

TIME=70*0., 0., 2.2, 3.3, 4.4, 5.5, 6.6, 7.7, 8.8, 9.9, 11., 50*0.,

0., 0.76, 1.14, 1.52, 1.9, 2.28, 2.66, 3.04, 3.42, 3.8,

0., 0.76, 1.14, 1.52, 1.9, 2.28, 2.66, 3.04, 3.42, 3.8,

TAUV=70*0., 1., 0.69, 0.53, 0.42, 0.29, 0.19, 0.12, 0.05, 0.01, 0., 50*0.,

1., 0.69, 0.53, 0.42, 0.29, 0.19, 0.12, 0.05, 0.01, 0.,

1., 0.69, 0.53, 0.42, 0.29, 0.19, 0.12, 0.05, 0.01, 0.,

*END

1	71.3	2.	1	0	0	2
11.950	18.5	42.8	0.	0.		
1	200	0	0	0	0	0
			2.5	200	3.6	80
						4.
						40

VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3
VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3
VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3

U	U	CCCC	FFFF
U	U	C	F
U	U	C	F
U	U	C	FFFF
U	U	C	F
U	U	C	F
UUUUU		CCCC	F

HH	HH	YY	YY	TTTTTTTTTT	RRRRRRRR	AAAAAA	NN	NN
HH	HH	YY	YY	TTTTTTTTTT	RRRRRRRR	AAAAAA	NN	NN
HH	HH	YY	YY	TT	RR	RR	AA	NN
HH	HH	YY	YY	TT	RR	RR	AA	NN
HH	HH	YY	YY	TT	RR	RR	AA	NNNN
HH	HH	YY	YY	TT	RR	RR	AA	NNNN
HHHHHHHHHH	YY	TT	RRRRRRRR	AA	AA	NN	NN	
HHHHHHHHHH	YY	TT	RRRRRRRR	AA	AA	NN	NN	
HH	HH	YY	TT	RR	RR	AAAAAAAAAA	NN	NNNN
HH	HH	YY	TT	RR	RR	AAAAAAAAAA	NN	NNNN
HH	HH	YY	TT	RR	RR	AA	AA	NN
HH	HH	YY	TT	RR	RR	AA	AA	NN
HH	HH	YY	TT	RR	RR	AA	AA	NN
HH	HH	YY	TT	RR	RR	AA	AA	NN

RRRRRRRR	PPPPPPP	TTTTTTTT	1111	55555555	55555555
RRRRRRRR	PPPPPPP	TTTTTTTT	1111	55555555	55555555
RR	PP	TT	1111	55	55
RR	PP	TT	1111	55	55
RR	PP	TT		555555	555555
RR	PP	TT		555555	555555
RRRRRRRR	PPPPPPP	TT	1111	55	55
RRRRRRRR	PPPPPPP	TT	1111	55	55
RR	PP	TT	1111	55	55
RR	PP	TT	1111	55	55
RR	PP	TT	11	55	55
RR	PP	TT	11	55	55
RR	PP	TT	11	555555	555555
RR	PP	TT	11	555555	555555

U	U	CCCC	FFFF
U	U	C	F
U	U	C	F
U	U	C	FFFF
U	U	C	F
U	U	C	F
UUUUU		CCCC	F

VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3
VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3
VAX/VMS	UCF	HYTRAN	6-JUL-1983	16:35	LPA0:	6-JUL-1983	16:36	DISK\$VAXVMSRL3

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HYTRAN INPUT DATA

LOX PRESSURE SPIKES WITHOUT VAPOR CAVITY COLLAPSE

```

$DIN
NJCT      =      22,
NPIPE     =      22,
DELT      = 2.4999999E-03,
TMAX      = 5.000000 ,
NP        =      1, 11*2,      3, 3*2,      3, 4*2,      1,
B*O,
NSORCE    =      1, 29*0,
NSINK     = 2*0, 2*3,      0,      3,      0,      1,
3*0,      3,      0, 2*1,      3,      0,      5,
0,      3,      0,      4, B*O,
NSTANK    = 4*0,      1,      0,      2, 23*0,
HT        = 2*246.7000 , 246.2000 , 232.6000 , 232.0000 ,
228.1000 , 228.0000 , 223.9000 , 206.5000 , 202.6000 ,
168.4000 , 68.00000 , 67.40000 , 66.90000 , 67.30000 ,
2*65.00000 , 55.90000 , 54.10000 , 3*53.20000 , B*0.0000000E+00,
C1P       = 30*0.0000000E+00,
C2P       = 30*0.0000000E+00,
C3P       = 246.7000 , 29*0.0000000E+00,
C4P       = 30*0.0000000E+00,
VOL       = 4*0.0000000E+00, 0.8300000 , 0.0000000E+00, 0.5000000 ,
23*0.0000000E+00,
VOLMIN    = 4*0.0000000E+00, 1.0000000E-03, 25*0.0000000E+00,
VOLMAX    = 4*0.0000000E+00, 2.700000 , 25*0.0000000E+00,
GAMMA     = 4*0.0000000E+00, 1.400000 , 25*0.0000000E+00,
CD        = 4*0.0000000E+00, 131.7000 , 25*0.0000000E+00,
XLI       = 4*0.0000000E+00, 30.00000 , 0.0000000E+00, 24.00000 ,
23*0.0000000E+00,
DLI       = 4*0.0000000E+00, 0.1660000 , 0.0000000E+00, 0.5000000 ,
23*0.0000000E+00,
FLI       = 4*0.0000000E+00, 9.9999998E-03, 0.0000000E+00, 2.0000000E-02,
23*0.0000000E+00,
KK        = 30*0,
D         = 1.416000 , 5*0.6670000 , 8*0.5000000 , 3*0.2500000 ,
2*0.5000000 , 2*1.000000 , 30.00000 , 18*0.0000000E+00,
XL        = 103.0000 , 5.100000 , 10.20000 , 25.50000 ,
94.50000 , 6.300000 , 26.20000 , 183.4000 , 39.30000 ,
366.8000 , 1061.100 , 7*6.550000 , 19.65000 , 6.125000 ,
30.62500 , 34.75000 , 18*0.0000000E+00,
VO        = 2.307000 , 5*10.42000 , 6*18.52000 , 2*17.90000 ,
3*2.470000 , 2*18.52000 , 2*4.630000 , 4.9999999E-03,
18*0.0000000E+00,
A         = 2410.000 , 3*1000.000 , 2*2500.000 , 13*2585.000 ,
3*2440.000 , 18*0.0000000E+00,
ALPHA     = -70.51000 , 2*-21.87000 , -90.00000 , -3.700000 ,
0.0000000E+00, -6.570000 , 0.0000000E+00, -90.00000 , -5.110000 ,
-0.1240000 , 30.25000 , 5*0.0000000E+00, -27.26000 ,
2*0.0000000E+00, 10.25000 , 90.00000 , 18*0.0000000E+00,
JJ        = 2*1,      2,      3,      4,      5,      6,
7,      8,      9,      10,      11,      12,
13,      15,      16,      14,      18,      19,
20,      21,      22, 9*0,      2,      3,
4,      5,      6,      7,      8,      9.

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10, 11, 12, 13, 14, 16,

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17, 18, 19, 20, 21, 22,
21*0, 15, 3*0, 17, 73*0,
IC = -1, 21*1, 9*0, 20*-1, 21*0, -1, 3*0, 1,
73*0,
CV = 2*0.0000000E+00, 3500.000, 680.3000, 0.0000000E+00,
1800.000, 0.0000000E+00, 2000.000, 3*0.0000000E+00, 2000.000,
0.0000000E+00, 2000.000, 500.0000, 60.00000, 0.0000000E+00,
850.0000, 0.0000000E+00, 2530.700, 0.0000000E+00, 4500000,
B*0.0000000E+00,
ELEV = 222.4000, 125.3000, 123.4000, 119.6000,
94.10000, 2*88.00000, 2*85.00000, 45.70000, 13.00000,
10.70000, 5*14.00000, 3*11.00000, 16.45000, 51.20000,
B*0.0000000E+00,
N = 17, 2, 4, 10, 15,
1, 4, 28, 6, 56, 162,
7*1, 3, 1, 2*5, 18*0,
F = 22*8.8000000E-03, 18*0.0000000E+00,
NTAU = 7*0, 10, 5*0, 2*10, 15*0,
TIME = 71*0.0000000E+00, 2.200000, 3.300000, 4.400000,
5.500000, 6.600000, 7.700000, 8.800000, 9.900000,
11.00000, 51*0.0000000E+00, 0.7600000, 1.140000, 1.520000,
1.900000, 2.280000, 2.660000, 3.040000, 3.420000,
3.800000, 0.0000000E+00, 0.7600000, 1.140000, 1.520000,
1.900000, 2.280000, 2.660000, 3.040000, 3.420000,
3.800000, 150*0.0000000E+00,
TAUV = 70*0.0000000E+00, 1.000000, 0.6900000, 0.5300000,
0.4200000, 0.2900000, 0.1900000, 0.1200000, 5.0000001E-02,
9.999998E-03, 51*0.0000000E+00, 1.000000, 0.6900000, 0.5300000,
0.4200000, 0.2900000, 0.1900000, 0.1200000, 5.0000001E-02,
9.999998E-03, 0.0000000E+00, 1.000000, 0.6900000, 0.5300000,
0.4200000, 0.2900000, 0.1900000, 0.1200000, 5.0000001E-02,
9.999998E-03, 151*0.0000000E+00
$END

```

```

ISTOP RHO, LB/FT**3 VARPR, FT IRUN ISTART IDATPE ITANK1
1 0.71300E+02 0.20000E+01 1 0 0 2

RADTK1, FT XHIGH1, FT XHIGH2, FT TKLENG, FT VFLOIN, FT**3/S
0.11950E+02 0.18500E+02 0.42800E+02 0.00000E+00 0.00000E+00

```

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OUTPUT PARAMETERS--LPRT, ITPRNT, LPLT, ITPLT, LTAPE, ITTPE, TIME2, ITPR2, TIME3, ITPR3, TIME4, ITPR4
1 200 0 0 0 0 2.50 200 3.60 80 4.00 40

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SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.00000E+00 SEC

PIPE NO.	PRESSURE HEAD UP STREAM END PSI	PRESSURE HEAD DN STREAM END PSI	VELOCITY UP STREAM END FT/SEC	VELOCITY DN STREAM END FT/SEC	VAPOR CAVITY LENGTH FT
1	0.12032E+02	0.60833E+02	0.23070E+01	0.23070E+01	0.00000E+00
2	0.60110E+02	0.60994E+02	0.10420E+02	0.10420E+02	0.00000E+00
3	0.60803E+02	0.62572E+02	0.10420E+02	0.10420E+02	0.00000E+00
4	0.55951E+02	0.68296E+02	0.10420E+02	0.10420E+02	0.00000E+00
5	0.68280E+02	0.70258E+02	0.10420E+02	0.10420E+02	0.00000E+00
6	0.69369E+02	0.69300E+02	0.10420E+02	0.10420E+02	0.00000E+00
7	0.69319E+02	0.69588E+02	0.18520E+02	0.18520E+02	0.00000E+00
8	0.68775E+02	0.60263E+02	0.18520E+02	0.18520E+02	0.00000E+00
9	0.60159E+02	0.77794E+02	0.18520E+02	0.18520E+02	0.00000E+00
10	0.77687E+02	0.76839E+02	0.18520E+02	0.18520E+02	0.00000E+00
11	0.76945E+02	0.28833E+02	0.18520E+02	0.18520E+02	0.00000E+00
12	0.28371E+02	0.26434E+02	0.18520E+02	0.18520E+02	0.00000E+00
13	0.26440E+02	0.26156E+02	0.17900E+02	0.17900E+02	0.00000E+00
14	0.26193E+02	0.25909E+02	0.17900E+02	0.17900E+02	0.00000E+00
15	0.26440E+02	0.26430E+02	0.24700E+01	0.24700E+01	0.00000E+00
16	0.26391E+02	0.26380E+02	0.24700E+01	0.24700E+01	0.00000E+00
17	0.25252E+02	0.25241E+02	0.24700E+01	0.24700E+01	0.00000E+00
18	0.25252E+02	0.26434E+02	0.18520E+02	0.18520E+02	0.00000E+00
19	0.22232E+02	0.21320E+02	0.18520E+02	0.18520E+02	0.00000E+00
20	0.21340E+02	0.21332E+02	0.46300E+01	0.46300E+01	0.00000E+00
21	0.20895E+02	0.18152E+02	0.46300E+01	0.46300E+01	0.00000E+00
22	0.18196E+02	0.99028E+00	0.50000E-02	0.50000E-02	0.00000E+00

MAXIMUM HEAD (PSI)

SKID INLET : 0.68775E+02 AT T= 0.00000E+00 SEC
 SKID OUTLET : 0.70258E+02 AT T= 0.00000E+00 SEC
 ORBITER INLET : 0.55951E+02 AT T= 0.00000E+00 SEC

VOLTKT, VOLTKG, VOLTKL, C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY
 0.19201E+05 0.82996E+04 0.10902E+05 0.24670E+03 0.22240E+03 0.10300E+03 0.60588E+01

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SOLUTION OF FLUID SYSTEM TRANSIENT AT TIME= 0.50000E+00 SEC

PIPE NO.	PRESSURE HEAD UP STREAM END PSI	PRESSURE HEAD DN STREAM END PSI	VELOCITY UP STREAM END FT/SEC	VELOCITY DN STREAM END FT/SEC	VAPOR CAVITY LENGTH FT
1	0.12030E+02	0.59978E+02	0.22922E+01	0.22908E+01	0.00000E+00
2	0.59979E+02	0.61002E+02	0.10324E+02	0.10329E+02	0.00000E+00
3	0.60747E+02	0.62543E+02	0.10329E+02	0.10334E+02	0.00000E+00
4	0.56059E+02	0.68414E+02	0.10334E+02	0.10327E+02	0.00000E+00
5	0.68414E+02	0.70530E+02	0.10373E+02	0.10375E+02	0.00000E+00
6	0.69594E+02	0.69548E+02	0.10375E+02	0.10376E+02	0.00000E+00
7	0.67086E+02	0.67324E+02	0.18465E+02	0.18465E+02	0.00000E+00
8	0.66458E+02	0.57959E+02	0.18465E+02	0.18465E+02	0.00000E+00
9	0.57959E+02	0.75797E+02	0.18465E+02	0.18466E+02	0.00000E+00
10	0.75797E+02	0.75780E+02	0.18466E+02	0.18422E+02	0.00000E+00
11	0.75795E+02	0.29737E+02	0.18422E+02	0.18504E+02	0.00000E+00
12	0.28963E+02	0.26753E+02	0.18504E+02	0.18510E+02	0.00000E+00
13	0.26753E+02	0.26272E+02	0.17792E+02	0.17800E+02	0.00000E+00
14	0.25134E+02	0.24633E+02	0.17800E+02	0.17807E+02	0.00000E+00
15	0.26753E+02	0.26562E+02	0.28720E+01	0.28779E+01	0.00000E+00
16	0.26500E+02	0.26167E+02	0.28779E+01	0.28875E+01	0.00000E+00
17	0.24884E+02	0.24633E+02	0.28875E+01	0.28983E+01	0.00000E+00
18	0.24633E+02	0.25524E+02	0.18532E+02	0.18539E+02	0.00000E+00
19	0.21310E+02	0.19845E+02	0.18539E+02	0.18546E+02	0.00000E+00
20	0.19845E+02	0.19892E+02	0.46366E+01	0.46357E+01	0.00000E+00
21	0.19413E+02	0.17652E+02	0.46357E+01	0.46298E+01	0.00000E+00
22	0.17652E+02	0.99028E+00	0.51442E-02	0.14499E-01	0.00000E+00

MAXIMUM HEAD (PSI)

SKID INLET : 0.68840E+02 AT T= 0.75000E-02 SEC
 SKID OUTLET : 0.71477E+02 AT T= 0.25000E-01 SEC
 ORBITER INLET : 0.56529E+02 AT T= 0.14250E+00 SEC

DATA AT NJCT=1 (TANK) HAVE BEEN ADJUSTED

VOL TKT. VOL TKG. VOL TKL. C3P(1), ELEV(1), XL(1), DELX(1) ARE, RESPECTIVELY
 0.19201E+05 0.83014E+04 0.10900E+05 0.24670E+03 0.22240E+03 0.10300E+03 0.60588E+01

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